

PERMO-TRIASSIC PALEOGEOGRAPHY AND TECTONICS
OF THE SOUTHWESTERN UNITED STATES

by

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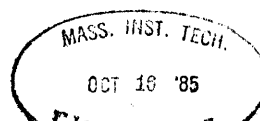
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ABSTRACT

Upper Permian and Lower Triassic rocks in the Mojave Desert and adjacent areas record the change from a passive margin to a subduction margin in the southwestern United States. This change was preceded by truncation of the continental margin and reorientation of the margin and paleogeographic trends in the Mojave Desert and western Basin and Range Province; areas to the east apparently were unaffected.

The western continental margin of North America trended northeast-southwest through Nevada and California from late Precambrian to Devonian time. During the Antler Orogeny in latest Devonian and earliest Mississippian time, eugeoclinal rocks were thrust onto the continental margin as a structurally complex package called the Roberts Mountain Allochthon. The position and nature of the continental margin changed during this event, but their overall trends were unaffected. The Roberts Mountain Allochthon became part of the continental margin of North America.

Processes leading to the truncation of the continental margin began in Pennsylvanian time when a strike-slip fault zone formed across the Antler belt and the miogeocline. A continental borderland developed in east-central California during this event. Rocks of the Roberts Mountain Allochthon and underlying slope-facies strata were displaced southward during the strike-slip faulting to their present position in the northwestern Mojave Desert; they are presently exposed in the El Paso Mountains, Pilot Knob Valley, and Lane Mountain area.

In Late Permian time a magmatic arc developed in the Mojave Desert on the displaced Roberts Mountain Allochthon rocks and on cratonal-miogeoclinal rocks in the Victorville area and San Bernardino Mountains (?). Magmatism was accompanied by deformation and metamorphism. The name Sidewinder event is proposed for this arc activity and deformation. The presence of magmatic rocks, deformation, and metamorphism in the western Mojave Desert may tie the displaced rocks into their present position by Late Permian time.

Marine sedimentation resumed in the Mojave Desert during a lull in arc magmatism in Early Triassic time. Deposition of Lower Triassic rocks in the western Mojave Desert took place in shallow-marine basins surrounding mountains and hills. In the eastern Mojave Desert sedimentation was in

shallow-marine basins only locally flanked by hills; relief is recorded by clasts derived from Precambrian crystalline rocks in Lower Triassic conglomerates in the Soda Mountains and Clark Mountains. In the Mojave Desert, lithofacies belts trend northwest-southeast while to the east of these areas lithofacies follow Paleozoic northeast-southwest trends.

The Lower Triassic rocks constitute an overlap sequence for the Sidewinder event and for juxtaposition of rocks of the Roberts Mountain Allochthon with rocks of the craton-miogeocline in the western Mojave Desert. The name Sidewinder overlap sequence is proposed for the Lower Triassic rocks. The presence of Lower Triassic rocks in the western Mojave Desert that are correlative with rocks to the east precludes large post-Early Triassic movements of the western Mojave Desert relative to the North American craton.

Arc magmatism resumed in Middle Triassic time. Volcanic and plutonic rocks of this age are present in the Victorville area, Soda Mountains, Devils Playground, Inyo Mountains, Argus Range, Saddlebag Lake area, Yerrington, and probably southeastern California and southern Arizona.

Upper Permian rocks related to the Sidewinder event in the western Mojave Desert record the first occurrence of Phanerozoic arc magmatism in the southwestern part of the United States. The Sidewinder event is older than the Sonoma Orogeny of Nevada. Lower Triassic rocks in the Mojave form an overlap sequence for the Sidewinder event; correlative rocks in Nevada are pre-tectonic to post-tectonic to the Sonoma Orogeny.

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CHAPTER 1: Outline of Problem

Introduction

An important topic in the study of orogenic belts is how and when major changes in tectonic setting occur. Examples of some major changes are: 1) the switch from subduction beneath southern California to transcurrent movements during the Cenozoic; and 2) the change from a passive continental margin to an active fold and thrust belt during the Mesozoic and early Cenozoic time in the Alpine chain of Switzerland. Such changes in tectonic setting are accompanied by corresponding changes in the physical geography of a region. Thus, we often infer tectonic setting from studies of paleogeography as interpreted from the rock record.

There is a major difference between the Paleozoic and Mesozoic tectonic settings along the western continental margin of North America. During most of Paleozoic time, the western edge of the North American craton was a west-facing passive continental margin (Stewart, 1970), except for a deformational event, the Antler Orogeny, that affected rocks on the outer shelf, slope, and rise during Devonian-Mississippian time. In contrast, during Mesozoic time, periods of eastward subduction beneath the Cordillera built an Andean-style arc along the margin.

Not only did the nature of the continental margin change, but the orientation of paleogeographic and tectonic trends changed as well. Hamilton and Meyers (1966, p. 513) first recognized that the Paleozoic miogeocline of western North America trends southwest across Nevada and southern California and that it is apparently truncated at an angle along the Pacific Coast and the San Andreas Fault. In addition, they observed that Mesozoic arc rocks are aligned northwest across the older Paleozoic trends, and that the difference between the Paleozoic and Mesozoic trends

is most pronounced in the Mojave Desert area of southern California. This led Hamilton (1969, p. 2412) to suggest that the southern continuation of the miogeocline, and hence the southwestern continental margin of the United States, was truncated by rifting in late Paleozoic or Triassic time. Burchfiel and Davis (1972, p. 106-107; 1981, p. 227-228) interpreted eugeoclinal rocks in the northwestern Mojave Desert, exposed in roof pendants in Mesozoic granitic rocks, to be out of place relative to the miogeoclinal trend. This led them to suggest that the margin was modified by strike-slip faulting in Permo-Triassic time following deposition of the sedimentary rocks in these miogeoclinal and displaced eugeoclinal sequences, but before intrusion of voluminous Mesozoic granitic rocks. These interpretations imply that the change from a passive margin to a subduction margin was complex and that there was an intervening event (or events) that trimmed off the southwestern edge of the North American craton.

The goal of this thesis is to investigate and interpret the timing and processes involved in the change from a passive to an active margin; this is one of the fundamental events in the development of the western United States. In order to resolve the timing and mechanisms of the modification of the tectonic setting and geometry of the continental margin of the western Cordillera, I have undertaken a study of late Paleozoic and early Mesozoic sequences in the Mojave Desert and the adjacent Basin and Range. The main focus of this study is to define Late Permian and Early Triassic paleogeography and structures for this region and to determine the tectonic setting of the margin at that time. Changes in paleogeography during that time record the modification of the margin. Earlier Permian and later Triassic rocks have been studied as well, and their paleogeographic and

tectonic settings have been interpreted. Unfortunately, Paleozoic and Mesozoic rocks in the Mojave Desert are usually preserved only as roof pendants in Jurassic and Cretaceous intrusive rocks. Thus, most of the sequences are metamorphosed, deformed, limited in areal extent, and far separated from rocks of similar age. This sometimes makes it difficult or impossible to correlate these sequences with absolute certainty. However, broad paleogeographic settings can be established for sequences around the Mojave Desert, based on their lithology, and by projecting tectonic elements into the area from surrounding regions containing better preserved strata.

Another important problem is to determine the timing of juxtaposition of the northwestern Mojave Desert siliceous (eugeoclinal) rocks with the cratonal and miogeoclinal rocks in the western Mojave. To do this, it is necessary to determine the oldest sequence of rocks that rests both on the displaced rocks and on miogeoclinal strata; such a sequence will be referred to as an overlap sequence. From this relation, tectonic juxtaposition is dated as being after the youngest rocks in each of the pre-overlap sequences and before deposition of the oldest rocks of the overlap sequence. Often overlap sequences are relatively isolated, in that they are not physically continuous across structures joining the different pre-overlap rocks; however, in most studies (and for the purposes of this study) establishing stratigraphic and age equivalence of lithologically similar rocks in isolated exposures is sufficient to demonstrate overlap. Another type of overlap sequence is one that rests on deformed rocks, where deformation can be dated as younger than the youngest deformed rocks and older than the oldest part of the overlap sequence.

In this study, I hope to demonstrate the age of juxtaposition of the displaced rocks in the northwestern Mojave Desert with the craton by means of an overlap sequence. Specifically, I want to show that there is a Lower Triassic overlap sequence that rests on both the out-of-place rocks and miogeoclinal rocks in the western Mojave (and that both Paleozoic assemblages were deformed and intruded in Late Permian time, prior to deposition of the overlap sequence), and that the overlap sequence is transitional to strata resting on miogeoclinal and cratonal rocks to the east.

With respect to the modification of the continental margin and displacement of the eugeoclinal rocks, we would like to know what tectonic processes are involved. Processes will be inferred from the study of the paleogeographic and tectonic affinity of the various rock sequences examined. Data on sections from the Basin and Range, the Mojave Desert, and the Colorado Plateau will be presented, and integrated into an interpretation of the late Paleozoic and early Mesozoic evolution of the southwestern part of the Cordilleran Orogen.

In the following text, I will: 1) describe the paleogeographic and tectonic problems to be addressed and geologic settings of regions examined; 2) present stratigraphic, structural, and geochronologic data, both those collected in this study and those in the literature; and 3) interpret these data for resolution of the tectonic problems.

Paleozoic Continental Configuration

One of the most important boundary conditions for this study is the configuration of the western part of the North American craton during Paleozoic time. Specifically, we need to know the geometry, and the

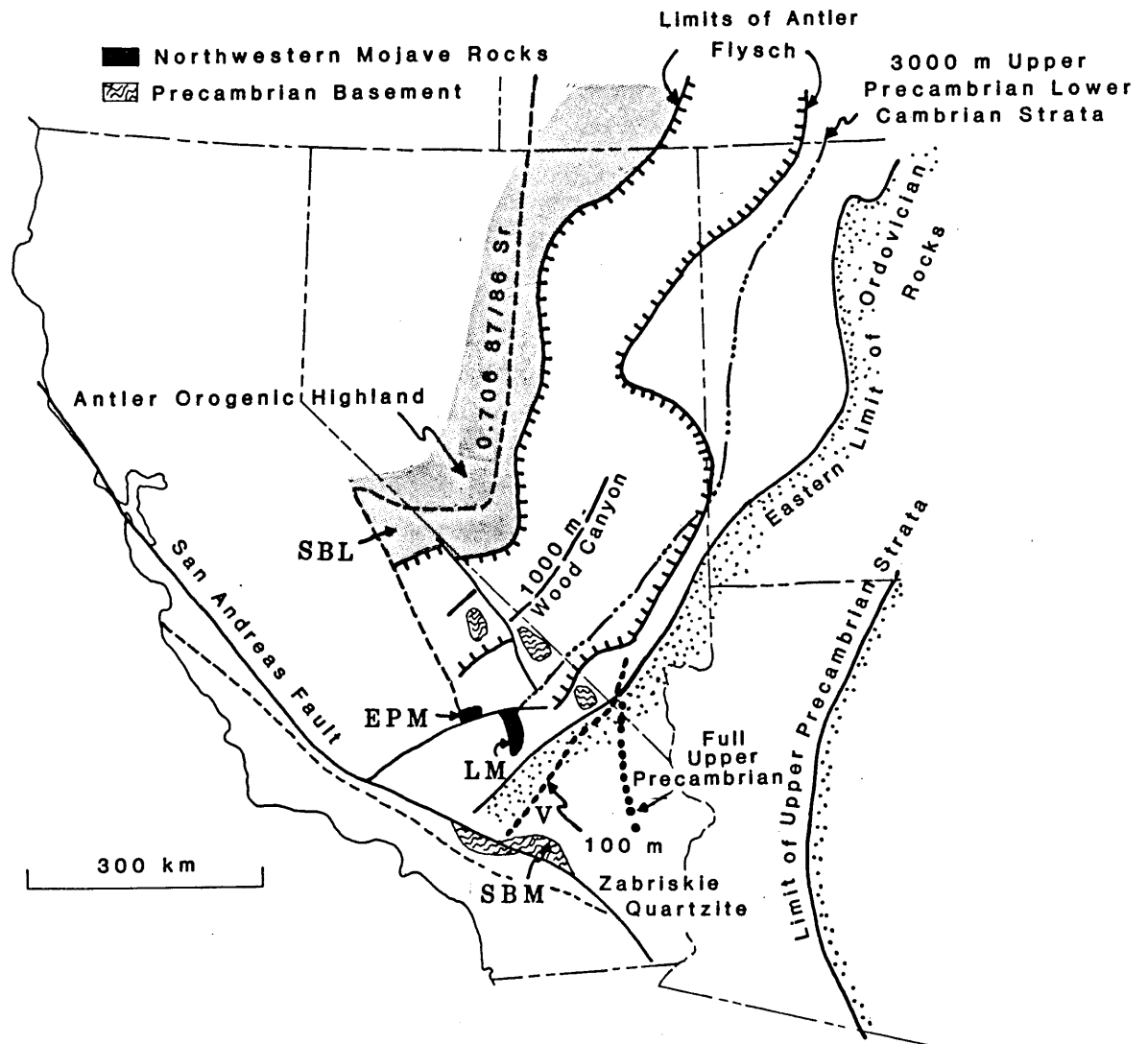
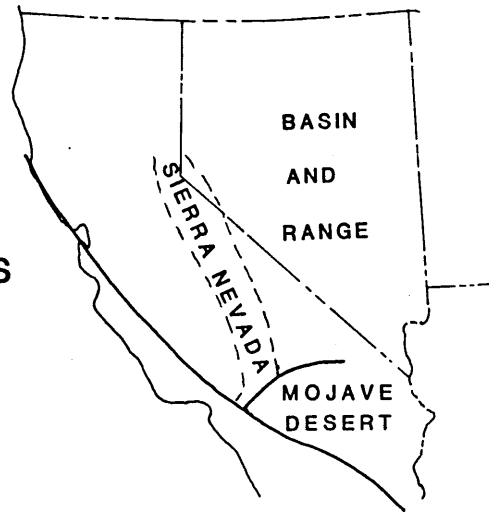
paleogeographic and tectonic settings of the western continental margin, and the western limit of North American Precambrian crystalline basement rocks. The important sources of data that help to define the western boundary of the North American craton and the position of the continental margin are: 1) the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of igneous rocks; 2) the facies distribution of Upper Precambrian and Paleozoic sedimentary rocks; and 3) the tectonic setting of Paleozoic rocks.

Initial $^{87}\text{Sr}/^{86}\text{Sr}$ Ratio of Igneous Rocks

Precambrian crystalline rocks crop out sporadically in the southwestern United States (Figure 1). We can, however, infer the extent of these rocks in the subsurface by studying the isotopic characteristics of intrusive and extrusive rocks, because the isotopic signatures of igneous rocks generated along active continental margins are thought to reflect the type of crust into which those igneous rocks intruded or passed through. In particular, the line separating Mesozoic plutons with initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios greater than 0.706 and less than 0.706 (Figure 1) is considered to delineate the western extent of Precambrian crystalline rocks which belong to cratonal North America (Kistler and Peterman, 1973, 1978). Plutons that ascend through Precambrian continental crust acquire $^{87}\text{Sr}/^{86}\text{Sr}$ initial values >0.706 ; values <0.706 indicate no old crustal influence in the plutons. As defined by the Sr 0.706 line, the configuration of the present western edge of the North American Precambrian crystalline rocks trends north-south through Nevada and swings westward into California. This line is offset by the San Andreas Fault, and lies in the Salinian Block and Peninsular Ranges to the west. A complicated pattern is present

Figure 1: Late Precambrian to Mississippian paleogeographic trends in the southwestern United States. EPM: El Paso Mountains; LM: Lane Mountain; SBL: Saddlebag Lake; SBM: San Bernardino Mountains; V: Victorville. Data from Burchfiel and Davis (1975, 1981), Cameron (1980), Kistler and Peterman (1973), E.L. Miller (1981), Poole (1974), and Stewart (1970).

Late Precambrian to Mississippian Paleogeographic Trends



in the southern Sierra Nevada, Great Basin, and the western Mojave Desert (Kistler and Peterman, 1978). Small individual variations in the initial ratios are probably unimportant, and only the gross trend of the 0.706 line need be considered.

Facies Distribution of Upper Precambrian and Paleozoic Rocks

The interpretation of the depositional environments of upper Precambrian and Paleozoic sedimentary rocks can be used to help define the western edge of the North American craton by locating the original position of the continental shelf, slope, and rise rocks, and sedimentary rocks deposited on oceanic crust. I will use the terms miogeocline and eugeocline proposed by Deitz and Holden (1966, 1974). Their usage will be slightly modified from that proposed by Stewart and Poole (1974, p. 29) for the western United States. "Miogeocline" describes the wedge-shaped deposits of upper Precambrian and Paleozoic rocks that thicken from the craton westward. "Eugeocline" describes lower Paleozoic siliceous and volcanic rocks that probably formed to the oceanward side (westward) of the miogeocline. Miogeoclinal rocks generally consist of upper Precambrian and lower Cambrian carbonates and terrigenous sedimentary rocks, and upper Cambrian to Permian platform carbonates and, locally, terrigenous rocks. Silurian and Ordovician rocks are missing toward the craton. Within the miogeocline and onto the craton, sequences containing a well developed upper Precambrian section but a thin Paleozoic section will be described by the term transitional-cratonal; sequences with thinly developed or missing upper Precambrian and incomplete Paleozoic sections will be referred to as cratonal; sequences that were deposited on the continental slope or outer shelf will be called transitional rocks. Lower Paleozoic eugeoclinal rocks

consist of Cambrian to Devonian siliceous terrigenous rocks, chert, and greenstone. These eugeoclinal rocks were thrust onto the continental edge during the Antler Orogeny in Late Devonian and Early Mississippian time, and became a positive topographic element (Antler Highland, Figure 1; Roberts, 1968), which shed debris into a flysch basin to the east. Mississippian to Permian eugeoclinal rocks were probably deposited in a basin that formed to the west of the Antler Highland.

Several stratigraphic features of the miogeoclinal Upper Precambrian and Lower Cambrian terrigenous and carbonate deposits are shown in Figure 1. The first two are 1) the depositional edge and 2) the 3000 m isopach of all rocks of this age (Stewart, 1970). These show clear north-northeast to south-southwest trends across the western United States and into the Mojave Desert. In fact, these trends can probably be extended smoothly to the San Andreas Fault. Also shown in Figure 1 is the line separating fully developed upper Precambrian and Lower Cambrian sequences (e.g., sequences easily divisible into typical Death Valley area units of Noonday Dolomite, Johnnie Formation, Stirling Quartzite, Wood Canyon Formation, Zabriskie Quartzite, and Cararra Formation) and thinner and more homogeneous sequences of this age (e.g., rocks mapped as Prospect Mountain Quartzite and Pioche Shale; Stewart, 1970; Burchfiel and Davis, 1981). Isopachs in the well developed sequences again indicate the northeast-southwest stratigraphic and paleogeographic trends through southern Nevada and California (Figure 1, Wood Canyon Formation 1000 m and Zabriskie 100 m isopachs; Stewart, 1970; E.L. Miller, 1981; Cameron, 1981). Lower Paleozoic rocks have similar facies trends (i.e., the depositional limit of Ordovician rocks, Figure 1).

Tectonic Setting

Eugeoclinal rocks of Cambrian to Devonian age were thrust eastward onto coeval shelf rocks during the Devono-Mississippian Antler Orogeny (Roberts and others, 1958; Burchfiel and Davis, 1972, p. 100). Eugeoclinal rocks were emplaced in a complexly imbricated and folded tectonic unit called the Roberts Mountain Allochthon. Emplacement created a highland, the Antler highland, on the western edge of the North American continent and a foredeep to the east which received deep-water to shallow-water, westward-derived clastic deposits. The eastern and western limits of Mississippian clastic rocks derived from the Antler Highland are shown in Figure 1. These deposits follow the same paleogeographic trend as the upper Precambrian and lower Paleozoic sequences. These data imply:

1) that the edge of the continent trended roughly northeast throughout late Precambrian to Mississippian time; and 2) the Antler Orogeny created a western source that supplied sediment into the Cordilleran miogeocline, and changed the position and tectonic nature but not the trend of sedimentary facies on the continental margin. Especially important is that no influence of the Antler Orogeny, such as the deposition of Mississippian clastic sedimentary rocks, has been detected in any of the western Mojave Desert miogeoclinal and cratonal sequences (E.L. Miller, 1981; Brown, 1984a).

I interpret the features described above and shown in Figure 1 as evidence of a northeast trend for the continental margin and the edge of North American Precambrian crystalline rocks across southern Nevada and into the Mojave Desert of California. Paleogeographic and lithofacies trends in Paleozoic time follow this pattern, and there is no indication that it was disturbed by the Devono-Mississippian Antler Orogeny. These

trends apparently end against the San Andreas Fault; the reconstruction of rocks west of the San Andreas is too uncertain to determine how the trends may continue to the west of the Mojave. Also, paleogeographic and isopach trends in the miogeoclinal rocks end against rocks in the westernmost and northwestern Mojave that are considered to be out of place relative to the trends described above.

Other authors have interpreted the relations described above differently. Poole (1974) suggested that eugeoclinal rocks in the northwestern Mojave are autochthonous, and form the southern continuation of the Antler and Sonoman (Permo-Triassic age) orogenic belts. Dickinson (1977, p. 140) proposed that the Mojave Desert area may have been a promontory created during late Precambrian rifting, and suggested that the western Mojave rocks are substantially in place, but owe their present position to telescoping along an irregularly shaped continental margin. Lastly, Stone and Stevens (1984a; oral communication, 1984) have proposed that the northwestern Mojave rocks are in place along a continental margin that originally trended north-south throughout late Precambrian and Paleozoic time, and that cratonal and miogeoclinal rocks in the western Mojave Desert (principally rocks in the San Bernardino Mountains and near Victorville) are actually out of place. These interpretations imply that there was a relatively simple transformation from a passive to an active margin in late Paleozoic time.

I do not favor these alternative interpretations because of evidence discussed above. The assumptions made in the rest of this thesis are that 1) the continental margin and craton edge trended northeast; 2) Precambrian crystalline and upper Precambrian and Paleozoic sedimentary rocks in the western Mojave Desert (specifically in the San Bernardino Mountains and

near Victorville, for locations of these areas see Figure 1 and 4) are the direct continuation of cratonal and miogeoclinal rocks exposed to the east; and 3) eugeoclinal rocks in the northwestern Mojave are out of place. This does not imply, however, that rocks in the western Mojave Desert have not moved relative to rocks farther east, only that any displacement is probably minor. Larger absolute movements, say relative to the Colorado Plateau, are not precluded. The justifications for these assumptions form most of the remainder of this chapter.

Margin Truncation

For the purposes of this thesis, I adopt the interpretation that a significant truncation event in late Paleozoic time trimmed off the southwestern part of the Cordilleran margin prior to the start of eastward subduction, and that the event probably started during late Paleozoic time. One of the best places to study this truncation event is in the Mojave Desert because 1) miogeoclinal and cratonal trends are continuous into the area, and 2) the earliest deformation of the craton following truncation, having occurred in Late Permian time, is present in this area. Also, the out-of-place rocks in the northwestern Mojave Desert help to determine the style and timing of margin truncation.

Northwestern Mojave Rocks and Antler Belt

The out-of-place sequence of lower Paleozoic eugeoclinal and transitional facies rocks present in the northwestern part of the Mojave Desert comprises lower Paleozoic volcanic rocks (greenstone) and siliceous sedimentary rocks, and upper Paleozoic volcanic and calcareous sedimentary rocks. These rocks are informally referred to as the northwestern Mojave

rocks. Principal outcrop areas are in the El Paso Mountains, at Lane Mountain, and in Pilot Knob Valley (Figure 1, 4). These rocks are out of place relative to miogeoclinal rocks immediately to the south and east: they probably represent a displaced fragment of the Roberts Mountains Allochthon, and hence do not fit logically into their present position in the northwestern Mojave (Figure 1; Burchfiel and Davis, 1981). As noted above, other authors consider these rocks to be in place. However, as their facies are different from adjacent rocks, some stratigraphic tie must be demonstrated to prove that they are in place. The oldest unambiguous tie is the Lower Triassic overlap sequence. No structures are presently exposed that are related to displacement of this sliver: any fault zones that were present are now intruded by Mesozoic plutonic rocks.

Northwestern Mojave rocks have been studied best in the El Paso Mountains. They comprise Cambrian (?) through Devonian greenstone and fine-grained siliceous rocks of eugeoclinal facies, and Ordovician turbidites, argillite, and greenstone of continental slope and rise facies (M.D. Carr and others, 1984; Poole and others, 1982). The sequence was imbricated in Devonian-Mississippian time during the Antler Orogeny (M.D. Carr and others, 1982, 1984). Upper Paleozoic stratigraphy of the northwestern Mojave sequence comprises Lower Mississippian conglomerate and argillite, Upper Mississippian (?) flysch, Pennsylvanian limestone and argillaceous turbidites, Lower Permian argillite with interbedded limestone turbidites, and Upper Permian tuffaceous sandstone and andesitic volcanic rocks. Siliceous rocks in the northwestern Mojave Desert have been correlated with rocks of the Antler Belt (M.D. Carr and others, 1981, 1982). Correlation of the El Paso Mountains sequence with the Roberts

Mountain Allochthon of the Antler belt is based on lithologic, paleontologic, and structural features that are identical in the northwest Mojave Desert and central Nevada (Poole, 1974).

The Antler belt trends north-south through northern and central Nevada and east-west through central Nevada (Mina area) into the roof pendants of the Sierra Nevada (Figure 1, Saddlebag Lake Pendant (SBL); Speed and others, 1977; Schweickert and Lahren, 1984). The out-of-place Mojave rocks are probably displaced 400 km from the north, since there is no indication that the Antler belt turned abruptly to the south in the Sierra Nevada, as assumed by Poole (1974). Further evidence supporting displacement of the out-of-place Mojave rocks is: 1) miogeoclinal and Antler trends show no evidence for change in orientation that would suggest that the Antler belt was continuous into the northwestern Mojave; 2) adjacent Mojave rocks contain no record of a nearby Antler deformation such as Mississippian foredeep deposits; and 3) in their present position, facies trends in northwestern Mojave rocks cut across early to middle Paleozoic miogeoclinal trends, while the Antler belt rocks throughout Nevada are parallel to the miogeoclinal trends.

An alternative hypothesis proposed by Stone and Stevens (1984a), similar to that of Poole (1974), is that northwest Mojave rocks are in place and miogeoclinal rocks of the western Mojave Desert, which I have used to define the trend of the Paleozoic continental margin, are out of place. They have suggested that the continental margin trended north to south from the Basin and Range Province into the Mojave, and that rocks at Victorville and in the San Bernardino Mountains are displaced from some southerly position (Paul Stone, oral communication, 1984). Stone and Stevens (1984a) base this interpretation on paleogeographic trends in

Pennsylvanian and Permian rocks in east-central California. However, older Paleozoic trends are at a high angle to the late Paleozoic trends they propose. I interpret the observed Pennsylvanian and Permian trends to result from processes leading to the truncation of the margin and not from the original geometry of the margin. This conclusion results from data summarized above, along with the additional observation that there is no structural or stratigraphic evidence that suggests that the western Mojave cratonal rocks have been radically displaced. The new trends interpreted by Stone and Stevens (1984a) for the Pennsylvanian and Permian rocks actually do support the interpretation that the northwestern Mojave rocks have been displaced, and give important insights into the processes of margin modification.

Early Arc Activity

Arc-related magmatism of Mesozoic age is well known in the western United States. The earliest arc activity can be dated as Late Permian in age, and is recorded by plutonic and volcanic rocks and associated deformational events in the Victorville area, in the El Paso Mountains, and at Lane Mountain (E.L. Miller, 1981; M.D. Carr and others, 1984). Deformation and arc activity of similar age may be present in the San Bernardino Mountains (Cameron, 1981) and at Cave Mountain (Figure 4; Cameron and others, 1979).

The Paleozoic stratigraphic sequence in the El Paso Mountains and at Lane Mountain contains upper Leonardian (?), Guadalupian (?), and younger andesitic volcanic rocks in its upper part (M.D. Carr and others, 1984). Following extrusion of these volcanic rocks, the entire sequence, at least in the El Paso Mountains, is folded, faulted, and intruded by a series of

syn- to post-kinematic plutons. One deformed pluton has been dated at 249 ± 3 Ma (U-Pb zircon) and others yield ages that place them as late Permian or Early Triassic (?) in age (M.D. Carr and others, 1984, p. 91-92; Cox and Morton, 1980). Transitional-cratonal rocks in the Victorville area were also deformed at this time, and are intruded by a post-kinematic monzonite dated at 242 ± 2 Ma (U-Pb zircon, J.E. Wright and E.L. Miller, oral comm., 1983). Axes of folds formed during the Late Permian deformation trend northwest (Miller, 1981; Carr and others, 1982). Upper greenschist grade metamorphism of Paleozoic and upper Precambrian rocks, as well as the presence of volcanic and plutonic rocks, suggest an arc setting for the Victorville area in Late Permian time (E.L. Miller, 1981). These data record the earliest Phanerozoic deformation and igneous activity on the craton, and possibly represent the earliest development of northwest tectonic and paleogeographic trends that became dominant in the southwestern part of the Cordillera during Mesozoic and Cenozoic time.

Outer Truncation

There must be an outer boundary to the displaced Antler rocks that would correspond to the "main" Permo-Triassic truncation of Burchfiel and Davis (1981, Figure 9-4). This implies that the Roberts Mountain Allochthon rocks in the northwest Mojave constitute a sliver of displaced material. Unfortunately, the geometry and location of the outer or main truncation is impossible to define because of later overprinting. The present western boundary of the northwestern Mojave sequence corresponds roughly with the Kings-Ritter break of Saleeby (1981), which formed during Mesozoic transcurrent tectonics.

Small outcrops of metamorphosed mafic volcanic and ultramafic rocks are present in the westernmost Mojave Desert (Figure 1; Dibblee, 1960). In the southern Tehachapi Mountains, probable Jurassic terrigenous sedimentary rocks and mafic flows are exposed (Dunne and others, 1975), along with nearby ultramafic rocks. These sequences may originally have been deposited west of both the North American craton and the displaced Antler rocks. The present position of these sequences may result from Jurassic transcurrent tectonics such as have affected the southern Sierra Nevada (Saleeby, 1981).

Precambrian and Paleozoic rocks are present south and west of the San Andreas Fault. Whether an outer truncation is preserved in these rocks is not known: the area is not studied well enough to determine paleogeographic trends.

Geologic Time Scale

Understanding of relevant biostratigraphic ages is important in dating sedimentary sequences. Figure 2 presents the most commonly used conodont and ammonite zones for the Early Triassic, as well as Permian and Early Triassic stage names to be used in this study.

Any attempt at correlating sequences whose dating is based variously on radiometric absolute ages and biostratigraphic relative ages requires some assumption about the geologic time scale. I present three time scales for the Permian-Triassic boundary based on the work of Harland and others (1982), Palmer (1983), and P.F. Carr and others (1984). These correlations are shown in Figure 2. I have adopted the date of P.F. Carr and others (1984) for the Permian-Triassic boundary because of their convincing arguments for the mathematical treatment that they used.

Figure 2: Names used for Permian and Lower Triassic series in this study.
Conodont stages from Carr and Paul (1983).

| SERIES | STAGES | CONODONT ZONES | AMMONITE BIOSTRATIGRAPHIC UNITS | ABSOLUTE AGES | | |
|-----------------|--------------|----------------------------|---|------------------------|-----|-----|
| MIDDLE TRIASSIC | ANISIAN | | Lenotropites caurus Zone | Carr and others (1984) | 240 | 243 |
| LOWER TRIASSIC | SPATHIAN | Neogondolella timorensis | Neopopanoceras haugi | | | |
| | | Neogondolella jubata | Prohungarites - Subcolumbites Beds | | | |
| | | Neospathodus Collinsoni | | | | |
| | | Neospathoudus triangularis | | | | |
| | SMITHIAN | Neospathodus waageni | Anasibirites Beds Meekoceras gracilitatis Zone | | | |
| | DIENERIAN | Neospathodus dieneri | | | | |
| | | Neospathodus kummeli | Protychites Beds | | | |
| | GRIESBACHIAN | Hindeodus typicalis | Claraia stachei Beds | | | |
| UPPER PERMIAN | OCHOAN | | | | 237 | 245 |
| | GUADALUPIAN | | | | | |
| LOWER PERMIAN | LEONARDIAN | | | | | |
| | WOLFCAMPIAN | | | | | |

Summary

The change from a northeast-trending passive continental margin to a northwest-trending subducting one can be best documented in the Mojave Desert. Prior to this change, the edge of the craton was truncated and material outboard of the Mojave was removed. Major questions to address, some of which have already been partially answered, and points to demonstrate are:

- 1) When did the out-of-place Roberts Mountain Allochthon rocks become juxtaposed with the western Mojave?
- 2) What was the timing of truncation of the craton, and how is it related to Late Permian igneous activity?
- 3) What was the paleogeography during Late Permian, Early, and Middle Triassic time in the western United States?
- 4) What was the tectonic evolution of the western United States during Permo-Triassic time?

CHAPTER 2: Regional Setting

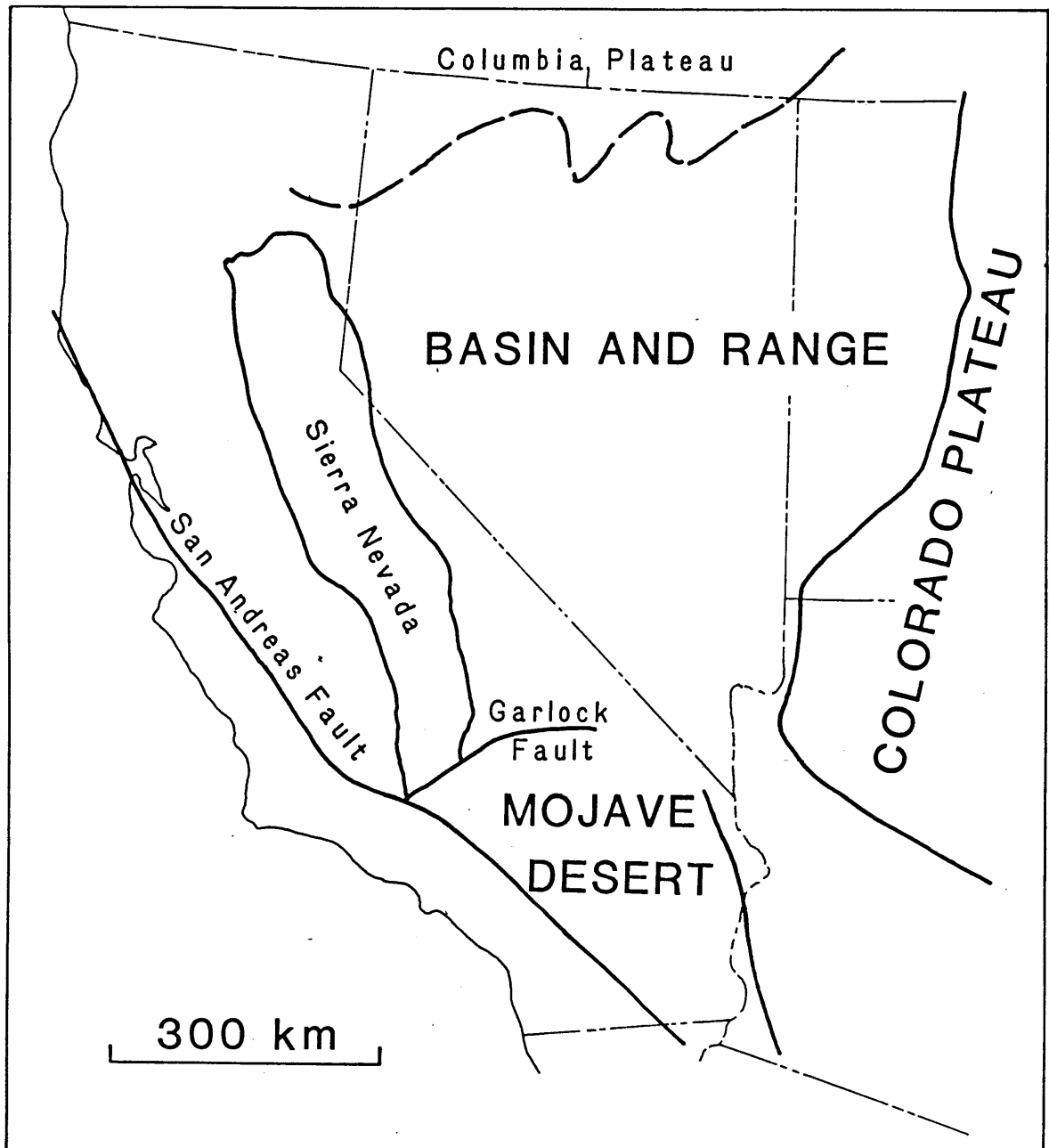
Introduction

This study encompasses the stratigraphy of rock sequences on the Colorado Plateau, in the Mojave Desert, and in the Basin and Range Province (Figure 3). Distinctions among these regions are made on structural differences. General structural, stratigraphic, and tectonic features of these areas are described below; detailed lithologic descriptions are given in the following two chapters.

Colorado Plateau Structural Block

The Colorado Plateau represents the little deformed cratonal interior to the Cordilleran belt (Figure 3). During Paleozoic time, this region was a lowland covered by relatively thin nonmarine and shallow-marine sedimentary deposits. Stratigraphic sections are cratonal in that they have thinly developed or missing upper Precambrian sequences and thin Paleozoic sections containing numerous unconformities. The Colorado Plateau has been a tectonically stable region since late Precambrian time, and deformation has been limited to minor thrust faulting and folding during the late Mesozoic Laramide Orogeny, and minor normal faulting in Cenozoic time. More importantly for this study, it was affected by large basement uplifts and adjacent basins formed during building of the Ancestral Rocky Mountains in late Paleozoic time. The latter event was probably in response to tectonic events related to the Ouachita orogenic system that developed along the southeast margin of the North American craton in the southern United States. These uplifts greatly influenced the pattern of sedimentation on the Plateau and in the eastern part of the Cordilleran Miogeocline. The limit of Cenozoic extensional deformation now

Figure 3: Structural blocks in the western United States referred to in this study.



serves to define the structural and physiographic edge of the Colorado Plateau; areas to the west, south, and east have been affected by normal faulting but the Plateau has remained relatively intact.

Mojave Desert Structural Block

The Mojave Desert structural block is separated by the Garlock Fault from the Basin and Range to the north, and is bounded to the west by the San Andreas Fault; its eastern boundary is arbitrary, and will be placed at the major breakaway zone of Cenozoic low-angle normal faults on its east side (Figure 3). Crystalline basement rocks and Paleozoic sedimentary rocks of the Colorado Plateau are continuous into the Mojave Desert (Figure 1). Paleozoic rocks in the eastern part of the Mojave are typical Grand Canyon/Colorado Plateau cratonal sequences (Stone and others, 1983, 1984; Brown, 1984b), and are on strike with facies trends on the Plateau. Upper Precambrian sedimentary rocks thicken to the west, but Paleozoic sequences are fairly uniform in thickness across the region. Sections are transitional-cratonal to the west in that they contain a well developed upper Precambrian and Paleozoic section; sections to the east are cratonal.

Deformation in the Mojave Desert began in Late Permian time and has continued intermittently to the present. The earliest deformational events affected mainly the western Mojave, and involved folding, faulting, metamorphism, and plutonism. The record of Mesozoic deformation is scattered owing to the voluminous granitic rocks that intrude the region. Cenozoic deformation has involved strike-slip faulting and extensional faulting that is locally of large magnitude (Dokka and Glazner, 1982; Davis and others, 1980, Dokka, 1983).

Basin and Range Province

The Basin and Range Province is the area between the Garlock Fault, the Sierra Nevada, the Colorado Plateau, and the Columbia Plateau (Figure 3). Exposure in ranges throughout this area is excellent. Paleogeographic trends are correspondingly well defined, although relations are locally ambiguous due to Cenozoic cover. Sequences can be divided into two types: 1) miogeoclinal deposits, which are transitional into cratonal rocks of the Colorado Plateau to the east, and 2) accreted oceanic/eugeoclinal sequences in the western Basin and Range Province. The Roberts Mountain and Golconda Thrusts form the boundary between the two kinds of sequences. A structurally complex assemblage of upper Paleozoic eugeoclinal rocks and island-arc (?) rocks called the Golconda Allochthon and Sonomia rest on the western part of the Roberts Mountain Allochthon. Both Mesozoic compressional and Cenozoic extensional tectonics affected the Basin and Range Province. Pennsylvanian and Permian age deformation is also important: depositional setting and facies trends changed significantly at this time in the southwestern part of the Basin and Range, and Permian rocks in east-central California record a complicated depositional history of numerous deep isolated basins that received sediments from bordering highlands (Stone and Stevens, 1984a).

CHAPTER 3: Southern Nevada and Mojave Desert

Introduction

This chapter presents data on important sections of Permian and Triassic rocks from the Colorado Plateau to the western side of the Mojave Desert. These areas were reexamined and/or mapped in detail in this study; descriptions are therefore necessarily detailed. Figure 4 is the location map for all of the sections given in this chapter. Figure 5 is a key to patterns used on stratigraphic columns. The main focus of this chapter is on Permian and Triassic rocks, but older and younger rocks will also be discussed as necessary. Related sections to the north and south will be reviewed in the next chapter.

Permian rocks in the Mojave Desert typically consist of cherty carbonates with terrigenous horizons of varying thickness. Lower Triassic rocks often comprise a two-part sequence consisting of a lower unit of limestone and siltstone and an upper quartz-rich unit.

Colorado Plateau

A relatively thin sequence of rocks of cratonic affinity is preserved on the Colorado Plateau in southwestern Utah and Arizona. Details on Permian sections in this area have been reviewed most recently by Blakey (1980) and Peterson (1980); information on Triassic sections comes mainly from Carr and Paull (1983), Blakey and Gubitosa (1983), Stewart and others (1972a, 1972b), and Cadigan (1971). A generalized stratigraphic column for Permian and Triassic rocks is shown in Figure 6.

Permian rocks generally consist of shallow-marine clastics and carbonates and nonmarine clastics. The Wolfcampian age Esplanade Sandstone forms the base of the Permian section in this area, and is interpreted as

Figure 4: Location map. CG: Cerro Gordo; CH: Cronese Hills; HH: Hinkley Hills; UW: Union Wash.

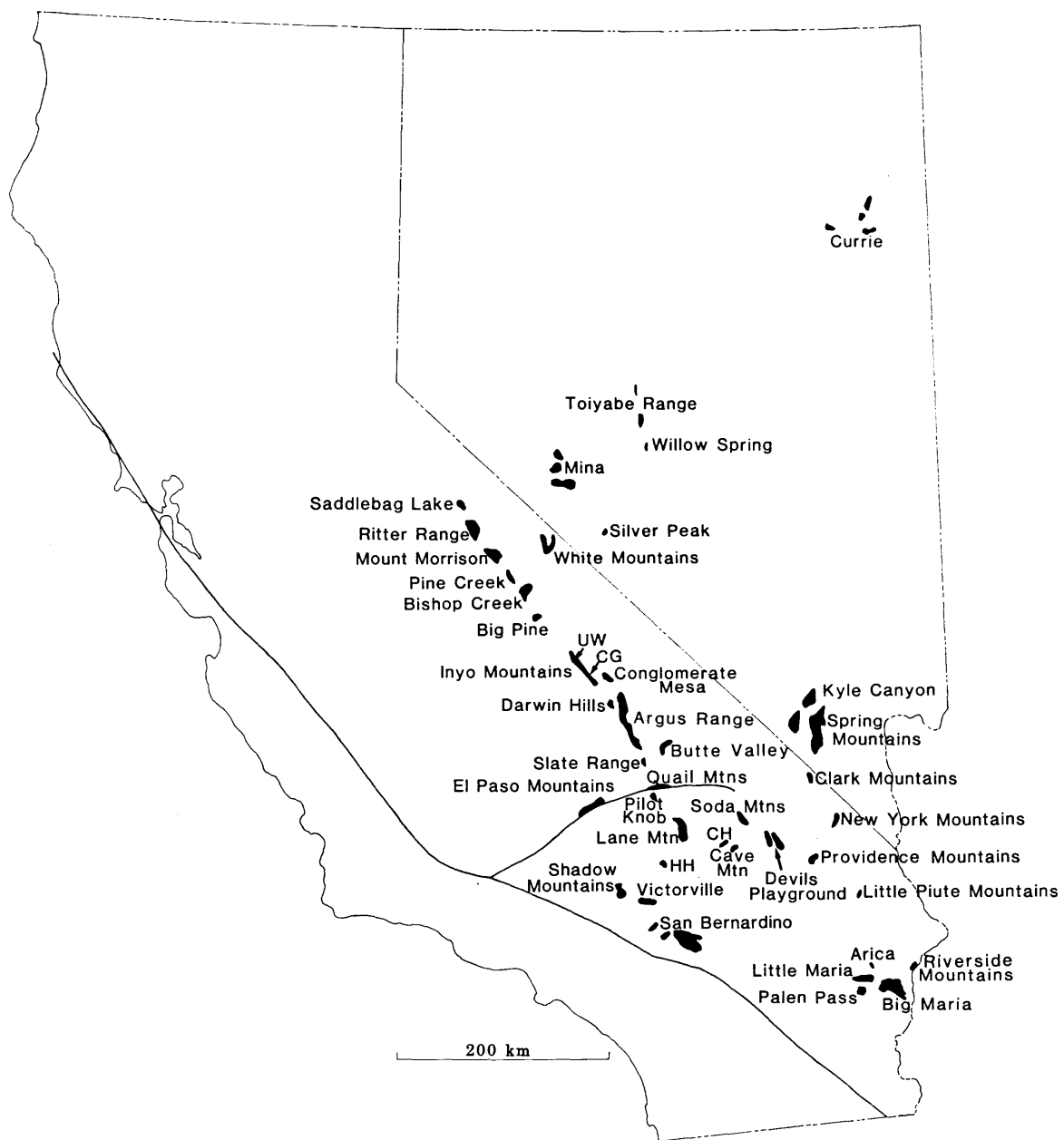
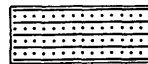


Figure 5: Key to patterns used for rock types in stratigraphic columns.

Key to Stratigraphic Columns



Quartz arenite



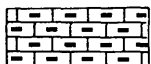
Sandy and silty argillite



Grit and conglomerate



Dolostone



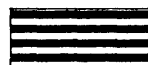
Cherty carbonate rock



Pillow lava



Conglomerate and arenite



Bedded gypsum



Plutonic rock



Sandstone



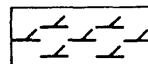
Shale, siltstone, schist



Volcanic rock



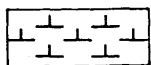
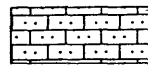
Shallow-water limestone

Large-scale cross
bedding present

Limestone Turbidites

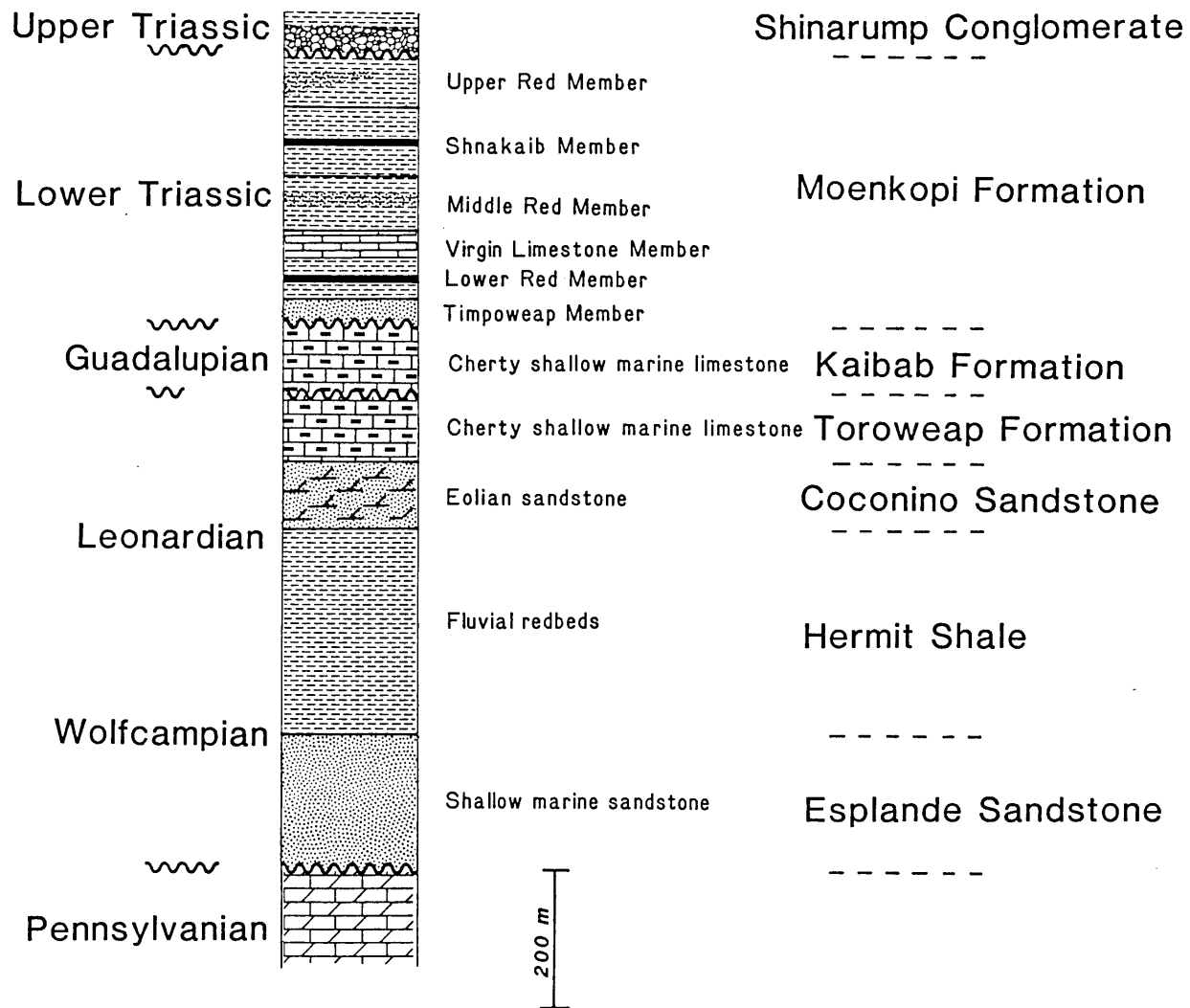


Conglomerate

Interbedded limestone
and dolostoneFeldspathic and
tuffaceous sandstoneCalcareous siltstone and
calc-silicate rock

Sandy and silty limestone

Figure 6: Grand Canyon section. From Stewart and others (1972b) and Blakey (1980).



having been deposited in a shallow marine, nearshore environment. The Esplanade Sandstone is overlain by the Hermit Shale, which comprises nonmarine to paralic red beds, and the succeeding Coconino Sandstone is of eolian origin. The youngest exposed Permian units are the Toroweap and Kaibab Formations of Leonardian to lower Guadalupian age. They comprise shallow-water cherty carbonate with minor interbedded sandstone and evaporite. The clastics in all of the Permian deposits were derived principally from the Uncompahgre Uplift to the northeast, and facies patterns indicate a general transition from marine to conglomeratic nonmarine rocks to the northeast (Peterson, 1980; Campbell, 1980).

The overlying Lower Triassic Moenkopi Formation is a westward and northward thickening sequence of nonmarine and marine clastics, evaporites, and carbonate (Figure 6). Stewart and others (1972b) have presented a very detailed description of the Moenkopi Formation throughout its outcrop area, and much of the information in this chapter comes from their work. The basal Timpoweap Member contains siltstone, sandstone, conglomerate, and minor limestone. The Timpoweap Member is overlain by silty red beds of the Lower Red Member. The middle part of the Moenkopi Formation consists of the Virgin Limestone Member, which comprises somewhat fossiliferous limestone and siltstone. The Moenkopi Formation is capped by silty and sandy red beds of the Middle Red, Massive Sandstone, Shnakaib, and Upper Red Members. Gypsum, both bedded and disseminated, is common throughout the Moenkopi Formation. The Moenkopi was deposited in fluvial systems to the east in Colorado and Utah, and to the south in central Arizona; the sequence thickens and becomes marine to the west.

Quartz and feldspar are the dominant detrital components in the Moenkopi Formation. One source area of arkosic terrigenous material is the

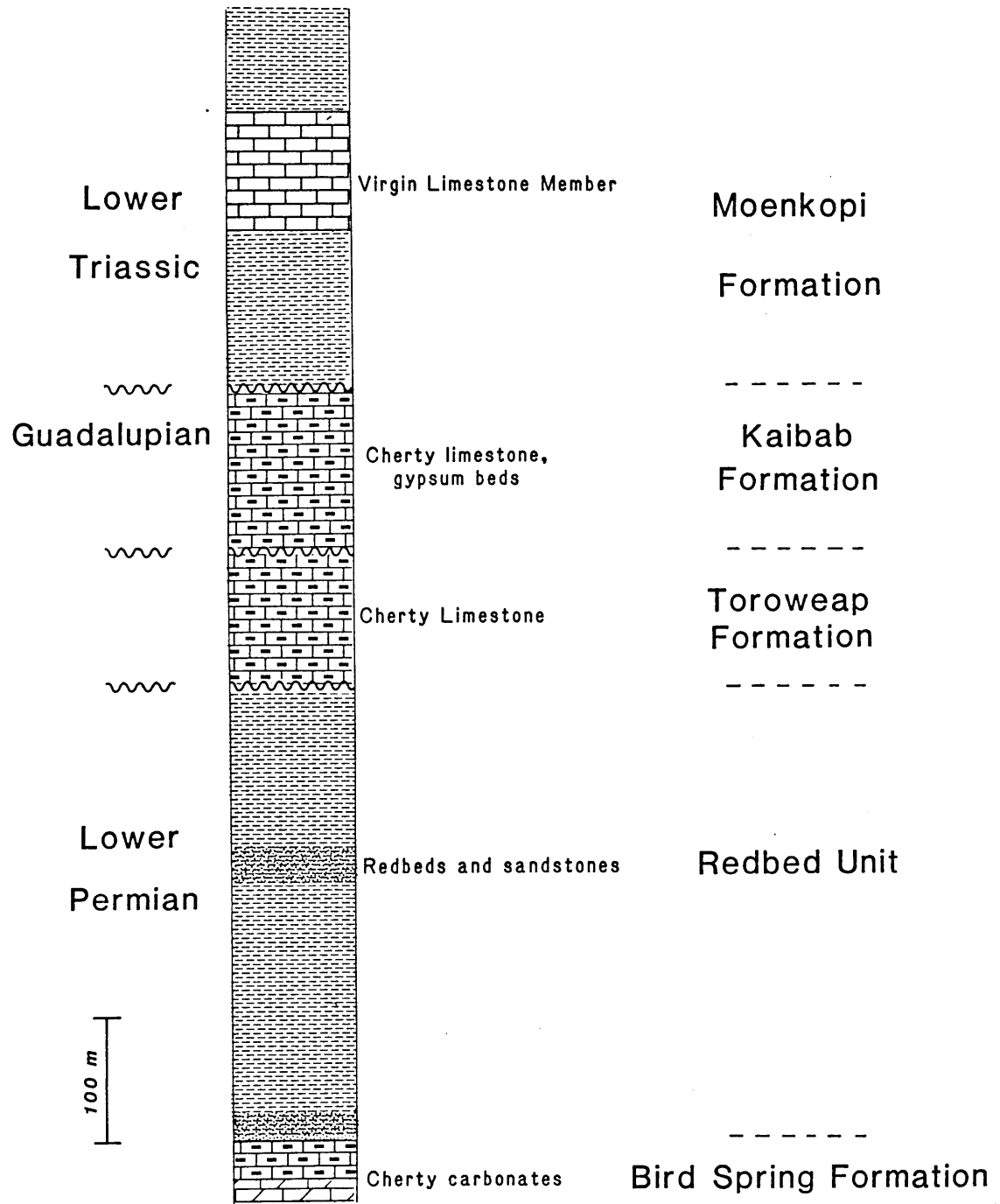
Uncompahgre Uplift of the Ancestral Rocky Mountains (the same area as for Permian clastics), but a southerly source in central Arizona is also indicated (Stewart and others, 1972b). Source areas are documented by facies changes, general coarsening of the Moenkopi Formation, and ultimately the presence of conglomerates in the section (Stewart and others, 1972b, p. 78-80). In Arizona, clasts in conglomerate units consist of chert, limestone, quartz, siltstone, and some quartzite probably derived from Permian rocks immediately underlying the Moenkopi. Calcite and dolomite are the most common cements, and calcite is the second most common component in the Moenkopi Formation (after quartz).

The age of the Moenkopi Formation is Early Triassic; dated material spans the Smithian and Spathian stages. Meekoceras and Anasibirites ammonite zones (Smithian) are present in the lower part of the formation, Tirolites zone in the Virgin Limestone Member, and Columbites zone (Spathian) at the top (Stewart and others, 1972b; see Figure 2 for a summary of ammonite zones).

Spring Mountains

Permian and Triassic rocks are exposed along the entire length of the Spring Mountains (Figure 4). Rocks of Permian age start in the carbonates of the Pennsylvanian-Permian Bird Spring Formation (Figure 7). Above the Bird Spring Formation are Leonardian (?) age red beds that are probably equivalent to the Hermit Shale of the Colorado Plateau. The red beds grade northward and up section into marine carbonates of Leonardian age (Burchfiel and others, 1974, p. 1015). The Permian section here is capped by the Toroweap and Kaibab Formations of Leonardian to Guadalupian (?) age.

Figure 7: Spring Mountains section. From Burchfiel and others (1974) and Longwell and others (1965).



Basal Triassic rocks in the Spring Mountains are assigned to the Moenkopi Formation (Longwell, 1925; Clark, 1957). Relative to exposures on the Colorado Plateau, the Moenkopi contains a thicker section of Virgin Limestone Member, and carbonate as a whole is more abundant (Clark, 1957). The upper and lower parts of this unit comprise red beds typical of the Moenkopi Formation. To the west, the Moenkopi Formation rests on progressively older Permian rocks, and chert-pebble conglomerate becomes common (Bissel, 1974, p. 93; Longwell and others, 1965, p. 38). In the Kyle Canyon area (Figure 4), the Moenkopi Formation contains abundant conglomerate at its base, and the sequence records shallow marine to nonmarine deposition throughout, suggesting westward shoaling and emergence of the area. Chert clasts are probably derived from cherty limestone of the underlying Kaibab Formation.

Clark Mountains

Permian rocks in the Clark Mountains are similar to those in the Spring Mountains, and the same threefold division (Bird Spring Formation, Red bed unit, and Kaibab Formation) is used (Burchfiel and Davis, 1971, unpublished data, Figure 7); the Toroweap Formation has not been mapped separately. The Moenkopi Formation here is similar to that on the western Colorado Plateau (Figure 6) with one major addition: conglomerate containing igneous and metamorphic rock clasts occurs in the Shnakaib Member (Walker and others, 1983). Clasts include granite, foliated granite, gneiss, intermediate volcanics, chert, and metasedimentary rocks. Current-direction data indicate northeast transport of clasts. Igneous clasts, particularly porphyritic volcanic rocks, may be derived from Upper Permian sections to the west, and the gneissic clasts indicate that

Precambrian rocks were uplifted during Late Permian or earliest Triassic time.

Providance Mountains

A sequence of Permian to Lower Triassic sedimentary and metasedimentary rocks is exposed in the northern Providence Mountains. This sequence was studied by Hazzard (1954; Figure 8). Permian rocks consist of limestone, cherty limestone, and dolostone of the Bird Spring Formation, and range up to Leonardian (?) age; the Kaibab Formation is missing here. The Bird Spring Formation is overlain by rocks equivalent to the Moenkopi Formation with an exposed thickness of 300 m. In the northern part of the northern Providence Mountains the basal unit of the Moenkopi Formation comprises 60 m of red-weathering sandstone and shale with locally abundant limestone-pebble conglomerate. The next unit consists of about 240 m of variably fossiliferous limestone with minor shale horizons. Fossils from this unit support an Early Triassic, probably Spathian, age assignment, but the Moenkopi Formation has not been dated in detail here. Most of this unit is lithologically equivalent to the Virgin Limestone Member of the Moenkopi Formation in southern Nevada. Importantly, this sequence has relatively more carbonate and no evaporite, so a deeper and more distal marine setting is indicated in comparison to sections of the Moenkopi Formation described above. In the southern part of the northern Providence Mountains, the Moenkopi is exposed in small outcrops that are faulted against the Bird Spring Formation to the south and intruded by the Fountain Peak Rhyolite to the north. Here the Moenkopi is contact metamorphosed and consists of calc-silicate hornfels.

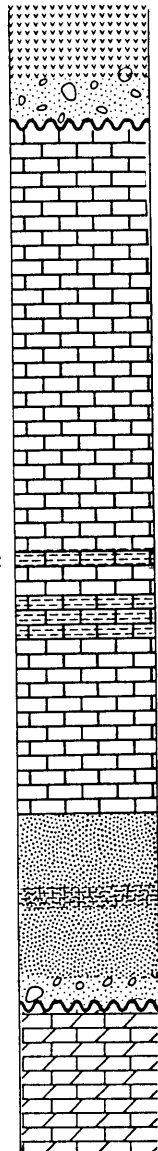
Figure 8: Section in the northern Providence Mountains. From Hazzard (1954) and this study.

Middle
Triassic (?)

50 m

Lower Triassic

Leonardian



Siliceous Volcanic Rock

Conglomerate

Light and dark gray weathering Limestone
Locally metamorphosed to
Calc-silicate Hornfels

Dark gray Limestone

Olivedrab weathering Shale

Gray to tan fossiliferous Limestone

Maroon to Brown weathering
Sandstone and Maroon Shale

Limestone-clast Conglomerate

Moenkopi
Formation

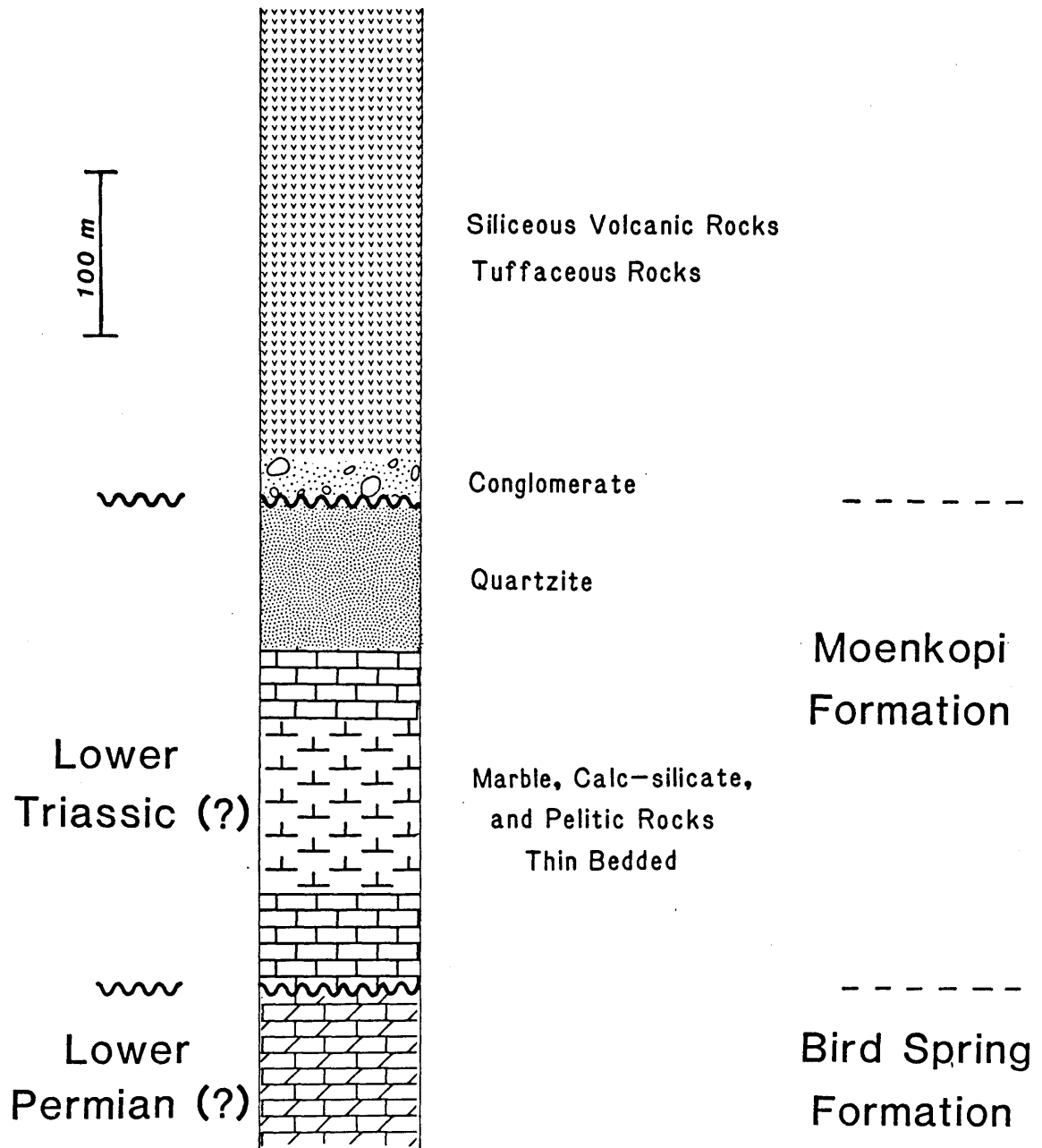
Bird Spring
Formation

The Moenkopi Formation is overlain by conglomerate and siliceous volcanic rocks. Hazzard (1954) correlated these rocks with dated Tertiary volcanic sequences to the northeast of this area. However, I interpret these volcanics to be of Middle or Late Triassic age because of their similarity to pre-Upper Cretaceous rocks in the New York Mountains (to be discussed below). The Fountain Peak Rhyolite, which forms the core of the Providence Mountains, is intruded into the Moenkopi-equivalent and volcanic rocks and was thus originally assigned a Tertiary age. However, the rhyolite is intruded by potassium-feldspar porphyry dikes that are similar to dated Middle Jurassic dikes in the region (David Miller, personal communication, 1983). Hence, the Fountain Peak Rhyolite and the volcanic and sedimentary rocks are probably of pre-Middle Jurassic age.

New York Mountains

A fairly complete upper Paleozoic to Mesozoic section is exposed in the New York Mountains (Burchfiel and Davis, 1977; Figure 9). Although the sequence is highly deformed and metamorphosed, correlations with dated rocks around the Mojave Desert can be made with confidence. Marble having a protolith of limestone, silty limestone, and dolostone correlates with the Pennsylvanian-Permian Bird Spring Formation. Unconformably (?) overlying these rocks is approximately 300 m of calc-silicate hornfels and quartzite with interbedded marble. Original thickness of the hornfels and quartzite is unknown owing to deformation in the area. Burchfiel and Davis assigned these rocks to the Moenkopi Formation, and my examination of this section supports this correlation. Samples of marble from this unit were collected and dissolved to recover conodonts; unfortunately, the samples were barren of microfossils.

Figure 9: New York Mountains Section. From Burchfiel and Davis (1977).

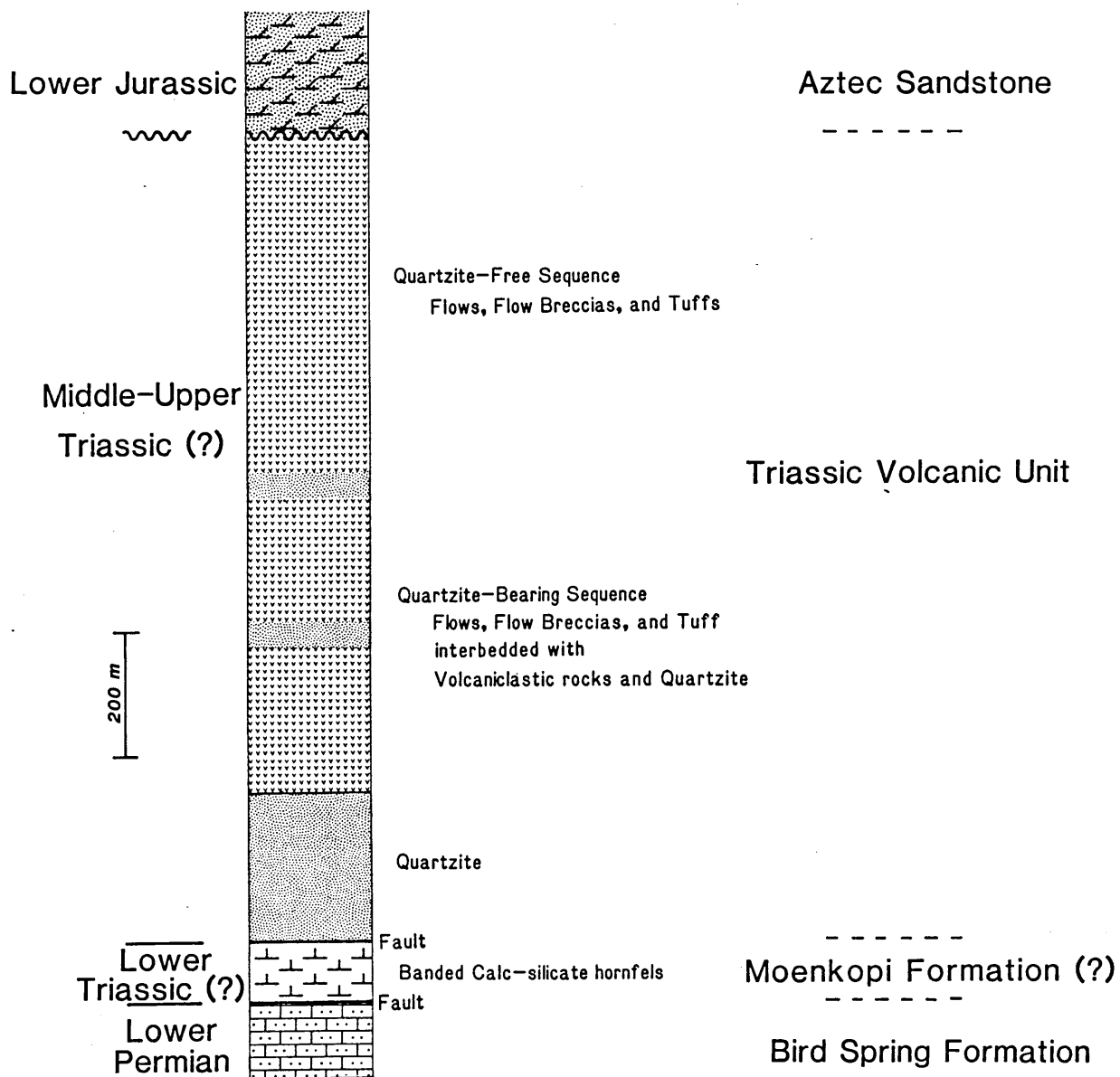


Rocks equivalent to the Moenkopi Formation comprise dark red-brown weathering calc-silicate rocks with local marble beds. Locally this sequence is capped by red, green, and gray quartzite with interbedded calc-silicate rock. (The presence of pure quartzite is common in the upper part of Lower Triassic sequences around the Mojave.) This unit is overlain unconformably by 300 m of conglomerate and siliceous metavolcanic rock consisting of quartz-plagioclase-potassium feldspar-biotite porphyry that resembles volcanic rocks in the Providence Mountains. In the New York Mountains these volcanic rocks are constrained as being pre-Upper Cretaceous in age (Burchfiel and Davis, 1977, p. 1633) and probably Triassic or Jurassic by correlation with rocks in the Providence Mountains.

Devils Playground

The Devils Playground area was recently studied by Dunne (1972, 1977), and was reexamined in this study (Figure 10). The Bird Spring Formation, which here ranges up to Lower Permian age (Dunne, 1972, p. 28), is the youngest Paleozoic unit exposed in the area. Mesozoic rocks comprise a thick but rather fragmented sequence, whose basal contact with Paleozoic rocks is not exposed in the area. Dunne assigned bedded calc-silicate rocks on the west side of Old Dad Mountain (on the west side of the Devils Playground area) to the Moenkopi Formation, and considered these rocks to form the base of the Mesozoic section. The Moenkopi-equivalent strata consist of thinly laminated to crossbedded calc-silicate hornfels which is probably derived from calcareous siltstone. Sedimentary structures in this unit, such as small-scale cross-stratification and hummocky cross-stratification, indicate a shallow-marine depositional setting for

Figure 10: Devils Playground section. From Dunne (1972, 1977).



this unit. Unfortunately, these rocks are not directly dated, and are bounded on one side by recent alluvium and on the other by a fault, so their exact thickness and relationship to other sequences is unknown. However, they are lithologically identical to other dated Lower Triassic rocks in the area, e.g., the metamorphosed section in the Providence and New York Mountains.

The calc-silicate rocks of the Devils Playground area were probably overlain depositionally by volcanic rocks of Dunne's Triassic Volcanic unit, although this contact is now a fault (Figure 10). The volcanic unit consists of a lower quartzite-bearing sequence at Old Dad Mountain and an upper quartzite-free sequence in the Cowhole Mountains on the west side of the Devils Playground area (Dunne, 1972, p. 32). The body of the lower unit consists of volcanic flows, flow breccias, and tuffs. Intercalated quartzites are up to 300 m thick and comprise quartz sandstone and shale. Dunne correlates this volcanic unit with the lower (pre-Aztec Sandstone) part of the Soda Mountain Formation, exposed in the Soda Mountains to the north. The Triassic Volcanic Unit in the Devils Playground area is also stratigraphically beneath the Lower Jurassic Aztec Sandstone, so it is reasonable to assign it a Middle and/or Upper Triassic age. Hence, quartzite in the Triassic Volcanic unit does not correlate with the Aztec Sandstone; rather, it constitutes a separate Triassic quartzite.

In addition to correlations of Early Triassic limestone and siltstone, which are probably equivalent to the Moenkopi Formation, the quartzite and quartz-rich sandstones associated with the Lower Triassic rocks are also an important component in the stratigraphic sequence. Quartzose sedimentary rocks are common in the upper part of these sequences, and constitute another widespread Lower Triassic unit. This upper quartzite

unit is present in the New York Mountains (in the upper part of the sedimentary section) and in the Devils Playground area (in the basal part of overlying volcanic rocks). In fact, a quartzite unit in this stratigraphic position is present in most of the Lower Triassic sequences within much of the Mojave Desert. Possible origins of this unit will be discussed below.

Soda Mountains

The Soda Mountains were mapped by Grose (1959), and the Spectre Spur part of the those mountains was remapped in this study; a detailed description of the geology of this area appears in Appendix A, along with a revised geologic map and a measured section of the Lower Triassic rocks. The main aim in remapping Spectre Spur was to study Permian and Lower Triassic rocks; Grose did not correctly correlate or recognize all of the Paleozoic and Triassic units on Spectre Spur because of metamorphism and complicated structures in the area. A fairly complete section of Cambrian to Jurassic rocks is exposed on Spectre Spur.

Permian rocks consist of Lower Permian (Wolfcampian?) carbonates of the Bird Spring Formation, and an overlying Leonardian age sequence of limestone, dolostone, chert, and silty carbonate rocks and their metamorphic equivalents (Figure 11). Sedimentary structures in these rocks, such as graded bedding with Bouma sequences and beds resembling debris flows, indicate deposition as sediment gravity flows, possibly in deep water. This sequence is similar in age and depositional setting to Lower Permian turbidite assemblages to the north and northwest in the Argus, Panamint, and Inyo Ranges, which have recently been described by Stone and Stevens (1984a). Conodonts recovered from the top of the

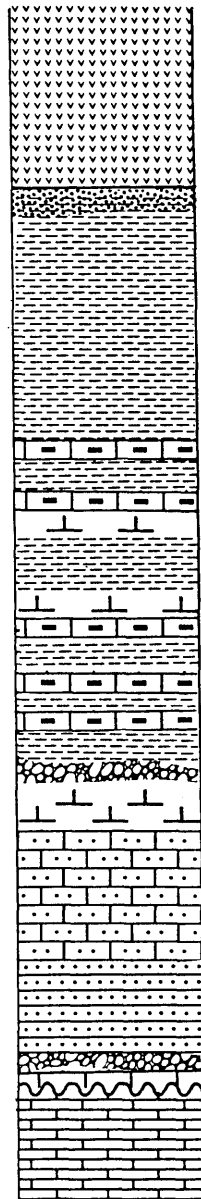
Figure 11: Soda Mountain section. From this study and Grose (1959).

Middle
Triassic

50 m

Spathian

Leonardian



Intermediate volcanic rocks

Red siltstone

Cherty limestone,
calcareous siltstone,
shale

Gastropod bearing

Ammonoid-bearing

Limestone and siltstone turbidites

Soda Mountain
Formation

Silver Lake
Formation

turbidite sequence in the Soda Mountains indicate a Leonardian age for these rocks.

Resting unconformably on the turbidites are Lower Triassic calc-silicate rocks, limestone and marble, and conglomerate. Conodonts recovered from limestone beds indicate a Spathian age for these rocks (see Appendix A). Small-scale cross-stratification, mud cracks, and channels indicate that the sequence was deposited in a shallow-marine setting. The upper part of this section comprises red sandstone and siltstone probably deposited in a fluvial setting. The Lower Triassic rocks have been named the Silver Lake Formation, after Silver Lake to the east of the Soda Mountains. This new name is proposed to emphasize lithologic differences (such as the presence of conglomerate, the absence of evaporite, and the generally more calcareous nature of the Soda Mountain rocks) between these rocks and time-equivalent strata of the Moenkopi Formation.

Conglomerates, which are present as thin to thick (10 cm to 10 m) beds and lenses, contain pebble-sized to cobble-sized clasts of limestone, chert, and volcanic and gneissic igneous rocks. Igneous clasts are minor, but their presence probably records uplift and volcanism in this area in pre-Spathian time. The upper sandstone and siltstone beds also contain volcanic debris. The overlying Soda Mountain Formation consists of andesitic flows, flow breccias, hypabyssal rocks, and sedimentary rocks; Grose (1959) interprets its contact with the Silver Lake Formation to be disconformable, but I interpret it to be conformable because the upper part of the Silver Lake Formation appears to be gradational into the Soda Mountain Formation. The upper part of the Soda Mountain Formation contains beds of eolian quartzite that have been correlated with the Lower Jurassic

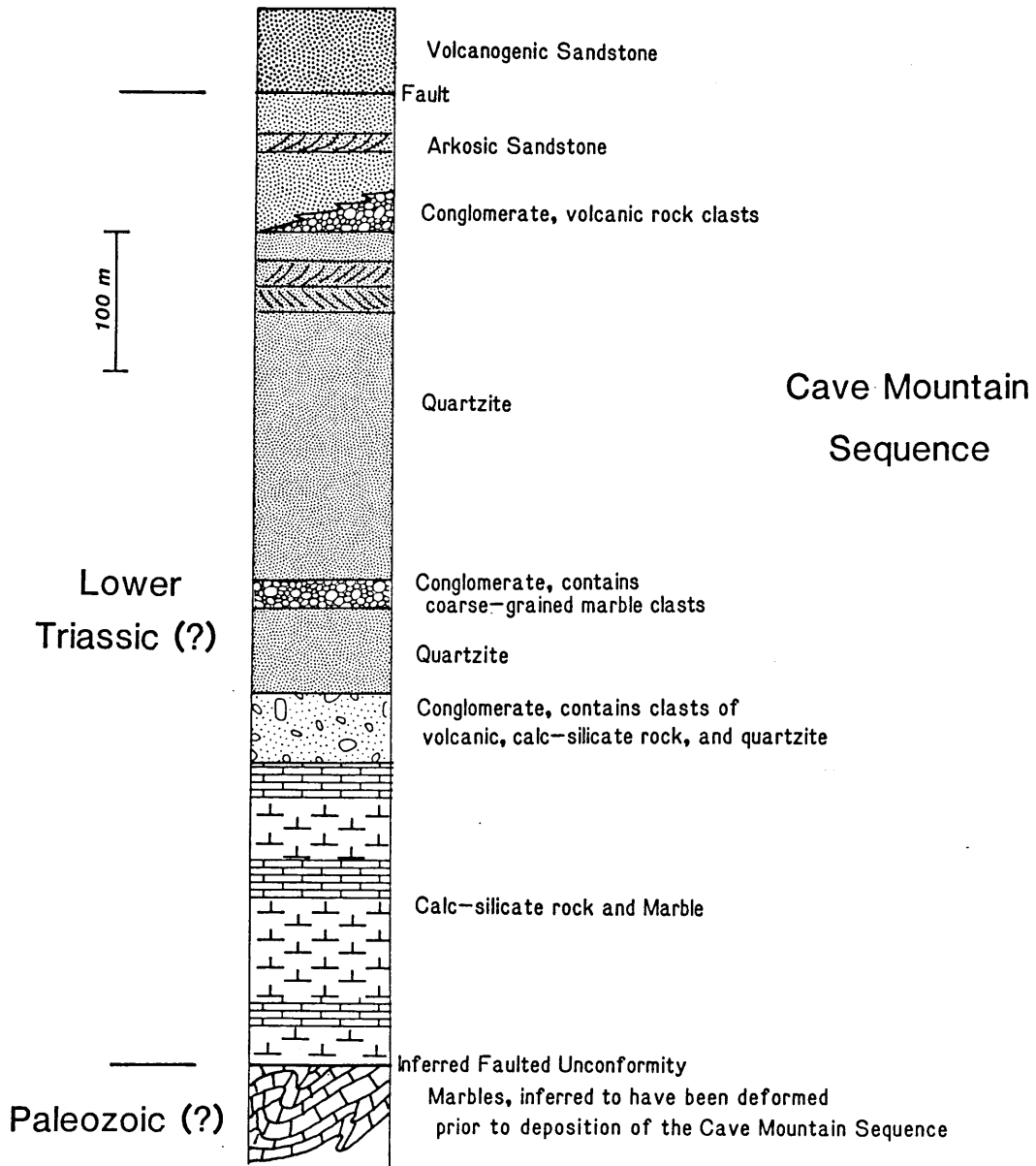
Aztec Sandstone (Grose, 1959; Marzolf, 1983). Hence the Soda Mountain Formation is assigned a Middle Triassic to Lower Jurassic age.

Cave Mountain

Fragmented, deformed, and metamorphosed rocks of the Cave Mountain Sequence are exposed near Cave Mountain and in the Cronese Hills (Figure 4). This sequence was studied by Cameron and others (1979) and by the writer in 1979, and was reexamined during this study. The Cave Mountain sequence near Cave Mountain comprises marble, bedded calc-silicate hornfels, metaconglomerate, quartzite, and meta-arkose (Figure 12). This sequence presumably rested unconformably on previously deformed and metamorphosed Paleozoic carbonate rocks, although now in fault contact, because marble clasts similar to the deformed carbonates are present in interbedded conglomerates of the Cave Mountain sequence. Conglomerate beds within this sequence contain clasts of volcanic rock, calc-silicate rock, marble, and quartzite. Sedimentary structures, such as low-angle cross-stratification, suggest shallow-water deposition of these rocks. Cameron and others (1979) correlated quartzite in this unit with the Lower Jurassic Aztec Sandstone to the east. However, the style of bedding is unlike the Aztec, and the quartzite resembles quartzite in Lower Triassic sequences to the east and west of this area. Hence, I correlate the entire Cave Mountain section with Lower Triassic rocks described above.

A 750 m thick sequence of quartzite-pebble conglomerate and calc-silicate rock is exposed in the Cronese Hills about 15 km northwest of Cave Mountain (Figure 4, CH). Sedimentary structures in this unit, such as channelling and mudcracks, suggest a shallow-water depositional setting. Whether these rocks were deposited entirely in a marine setting

Figure 12: Cave Mountain sequence. From Cameron and others (1979).



is doubtful, but the calc-silicate rock to the south contains interbedded marble, so some marine influence is likely.

Rocks exposed in the Cave Mountain area are not well dated. The metasedimentary rocks in the Cronese Hills are in fault contact with metavolcanic rocks, and faulting and metamorphism here is Middle Jurassic (B.C. Burchfiel, personal communication, 1984). Hence the Cave Mountain sequence is older than Middle Jurassic, and I assign it to the Lower Triassic because of its lithologic similarity to dated rocks to the east and west.

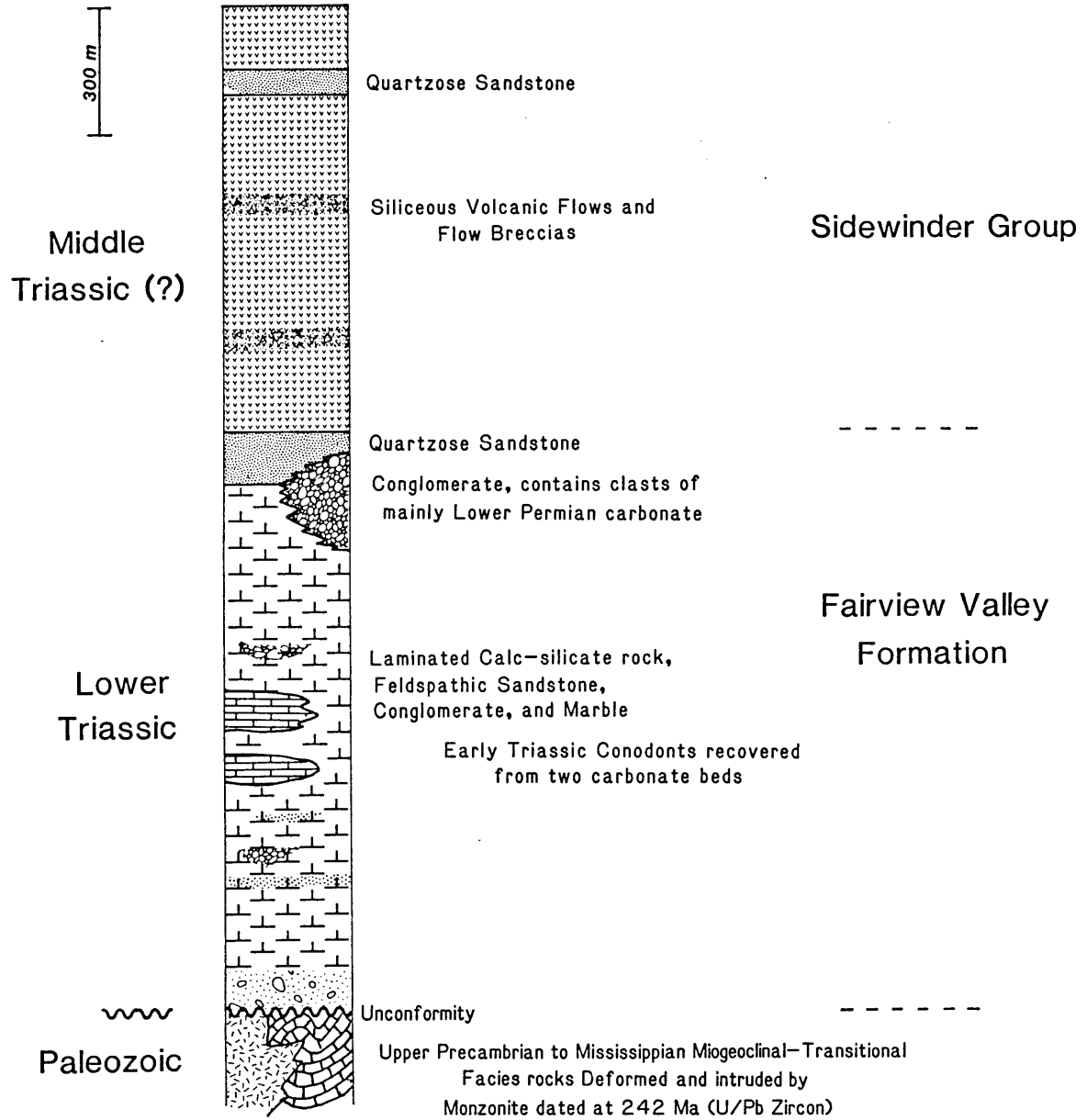
Victorville

The geology of the Victorville area was most recently studied by E.L. Miller (1977, 1978, 1981). Stratified rocks range from upper Precambrian to Mesozoic age; the upper Precambrian rocks are fully developed but the Paleozoic section is thin and incomplete. The youngest Paleozoic sedimentary rock exposed in the area is correlated lithologically with the Mississippian Monte Cristo Limestone; Pennsylvanian and Permian strata are probably present in this area, but are unrecognized because of metamorphism.

The Precambrian and Paleozoic rocks were deformed and metamorphosed in late Paleozoic time and were subsequently intruded by a monzonite pluton dated at 242 ± 2 Ma (U-Pb zircon, J. Wright, oral communication, 1983). Deformation is thus bracketed as post-Mississippian and pre-242 Ma, and is probably Late Permian based on regional considerations.

The monzonite pluton and deformed Paleozoic rocks are unconformably overlain by the Lower Triassic Fairview Valley Formation (Miller, 1981; Figure 13). The Fairview Valley Formation consists limestone and marble,

Figure 13: Section at Black Mountain near Victorville. From Miller (1977, 1981) and this study.



calc-silicate rock, metasandstone, and metaconglomerate, and is itself deformed and intruded by a suite of Mesozoic granitic rocks. Carbonate rocks are fine- to medium-grained, unfossiliferous, and occur in medium to thick beds. Conglomerate beds are generally lens-shaped and laterally discontinuous. Clasts include limestone, chert, granite, monzonite, gneiss, and volcanic rock. In the southern part of the outcrop area, a wedge of carbonate-clast conglomerate interfingers with the fine-grained carbonates. The conglomerate unit may record synsedimentary faulting during deposition of the Fairview Valley Formation. Clasts in this conglomerate are derived primarily from Lower Permian rocks, although rocks from most of the Paleozoic units are represented (Bowen, 1954, p. 41), and record the presence of Permian sedimentary rocks in the area even though none are recognized in the metamorphosed sequences. Sandstone in the Fairview Valley Formation is arkosic and contains abundant lithic clasts. Lithics include metaquartzite, chert, volcanics, and plutonic rock fragments. Clasts of sheared granitic rocks are present in both sandstone and conglomerate; Miller (1977, p. 77) interprets these to be derived from the Precambrian basement rocks in the area.

Calc-silicate rocks are generally thinly bedded and laminated and were probably derived from silty limestone and calcareous siltstone. Small-scale cross-stratification, burrows, and mud cracks indicate a shallow marine origin for these rocks. Conglomerate occurs within erosional channels and interbedded with fine-grained calc-silicate rocks. Miller (1977, 1978) interpreted the Fairview Valley Formation to represent rocks deposited in a shallow marine environment that interfingered with alluvial-fan deposits.

Prior to this study, the age of the Fairview Valley Formation was not well determined. Samples of carbonate beds were collected and dissolved to recover conodonts. One bed yielded the Early Triassic conodonts Ellisonia sp. and Neospathodus sp.; a second bed yielded a mixed-age fauna, the youngest of which were Early Triassic (B.R. Wardlaw, personal communication, 1984). Location of samples is shown in Figure 14, and a sample of conodont material recovered is shown in Figure 15. Based on these data, the Fairview Valley Formation is assigned an Early Triassic age. This age is also consistent with the age of the underlying monzonite (see Figure 2).

The Fairview Valley Formation is overlain by quartz-rich sandstone. Miller interpreted the contact between the Fairview Valley and this sandstone to be an unconformity. Reexamination of this contact, however, shows it to be conformable. Carbonate-clast conglomerate at the top of the Fairview Valley Formation (wedge-shaped package at Black Mountain) interfingers with the quartz sandstone, implying continuity of sandstone and Fairview Valley Formation deposition. Thus, this quartz sandstone unit is Lower or Middle Triassic in age, and probably does not correlate with the Aztec Sandstone, as interpreted by Miller.

The quartz-rich sandstone is overlain by at least 1000 m of volcanic and sedimentary rocks of the Sidewinder Group. Volcanic rocks consist of intermediate to siliceous flows and flow breccias. Quartz-rich sandstone is also present in the upper part of the Sidewinder Group (Miller, 1981, p. 580). The Sidewinder volcanic rocks have not been accurately dated, but DeLisle and others (1965) report lead-alpha ages of 230 ± 33 , 248 ± 25 , 267 ± 27 , and 252 ± 25 Ma for rocks in the Sidewinder Group. U/Pb analysis of zircon fractions from the lower part of the Sidewinder attempted by the

Figure 14: Location map of samples yielding conodonts in the Fairview Valley Formation.

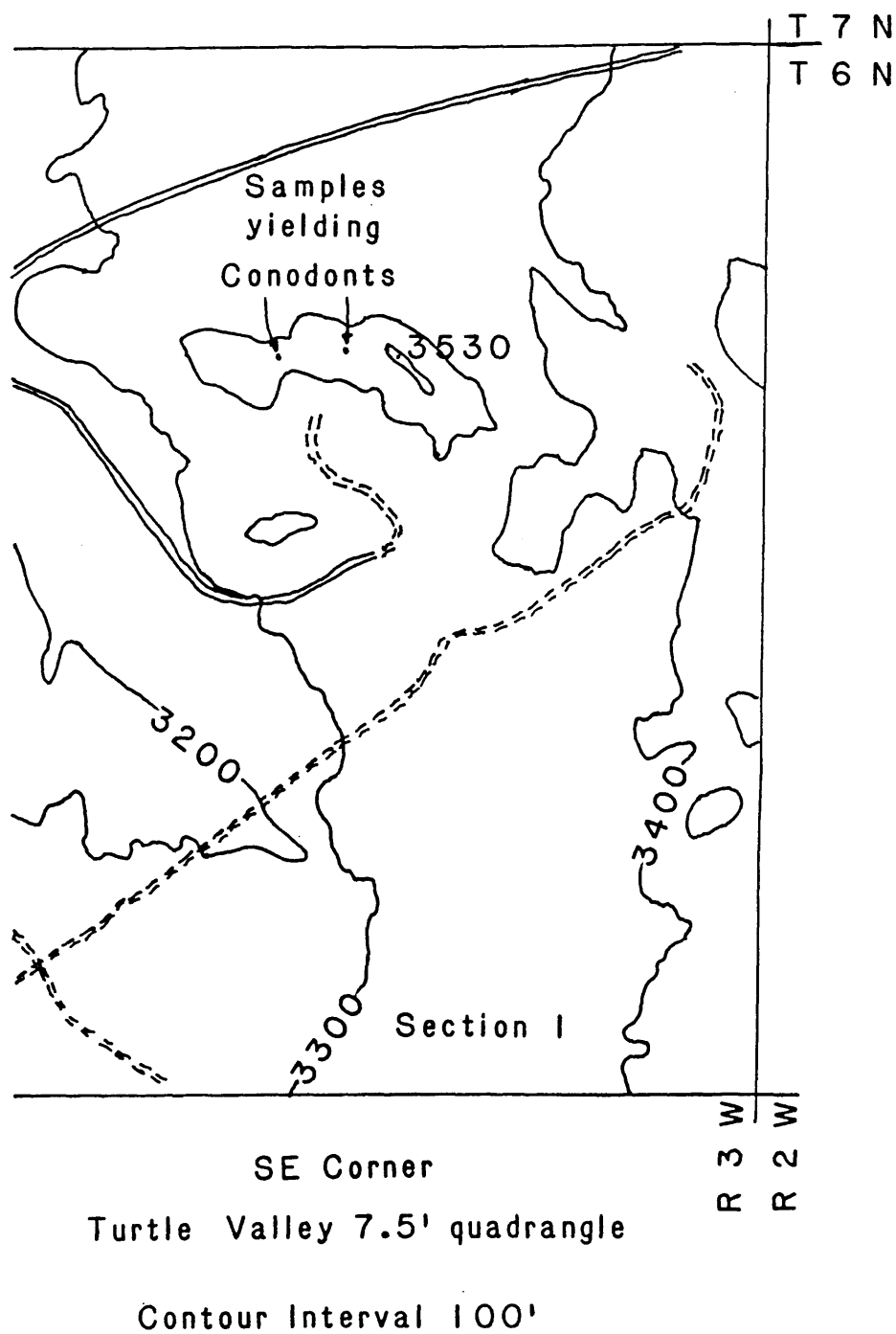
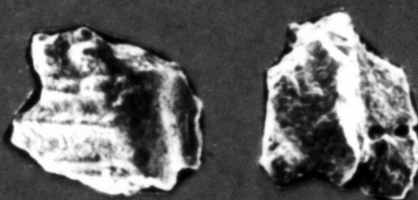
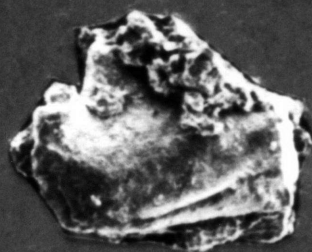


Figure 15: Sample of material recovered from the Fairview Valley Formation.
Identified by Bruce R. Wardlaw, United States Geological
Survey (personal communication, 1984).

FAIRVIEW VALLEY FORMATION




REWORKED PENNSYLVANIAN-PERMIAN CONODONTS



ELLISONIA

POORLY PRESERVED LOWER TRIASSIC CONODONT FAUNA

0.5 MM



author has been unsuccessful; the samples contain too much inherited lead and have a metamorphic history that is too complicated to yield a meaningful interpretation for the age.

Igneous rocks in the Victorville area, in particular the Late Permian monzonite, are key to interpreting the Late Permian and Triassic tectonic settings of the area. C.F. Miller (1978, p. 171-172) considered other Permo-Triassic plutonic rocks in the southern Cordillera to belong to an early alkalic arc built on the edge of North America. Miller infers that the alkalic nature of the early plutons in the Cordillera reflects the initiation of subduction-related magmatism. If this is true, these rocks record the start of igneous activity related to eastward subduction beneath the North American plate in Permo-Triassic time.

Shadow Mountains

A fragmented and metamorphosed sequence of Paleozoic rocks is exposed in the Shadow Mountains (Figure 4). The paleogeographic position and affinities of these rocks are very important: they appear to constitute the westernmost area of recognized North American miogeoclinal (?) rocks in the Mojave Desert. These rocks were studied by Bowen (1954), who reported a probable Pennsylvanian brachiopod from the eastern part of the area. Troxel and Gunderson (1970) remapped this area and assigned the rocks an upper Paleozoic age. Poole (1974, p. 64) correlated calc-silicate hornfels, schist, and thin marbles of the area with the Mississippian and Pennsylvanian (?) Antler flysch of Nevada and California. Flyschoid rocks are overlain by well layered to massive calcitic and dolomitic marble which Poole (1974) correlated with the Bird Spring Formation. In addition, Brown (1983) identified probable Cambrian miogeoclinal rocks of the Bonanza King

Formation in this area.

The paleogeographic affinity of these rocks is still uncertain, despite the studies concentrated on them. Whether the different assemblages are in structural or stratigraphic contact awaits further study.

Northwestern Mojave Rocks

Important exposures of Paleozoic and Mesozoic rocks are present in the El Paso Mountains north of the Garlock Fault, and in the Pilot Knob Valley and the Lane Mountain areas south of the Garlock (Figure 4). When movement is reversed on the Garlock Fault, these rocks form a north-south trending belt across the northern Mojave. Sequences in these areas are here termed the northwest Mojave assemblage or northwestern Mojave rocks. Lower Paleozoic rocks are eugeoclinal in character, and upper Paleozoic rocks are unlike those to the south and southeast. These rocks are best dated in the El Paso Mountains (Poole and others, 1982), and seem to have almost one-to-one equivalents in the Lane Mountain area (Carr and others, 1981, p. 17; M.D. Carr, personal communication, 1983). Because of their paleogeographic and tectonic importance, lower Paleozoic rocks will be described from this section as well as the upper Paleozoic and Mesozoic sequences.

El Paso Mountains

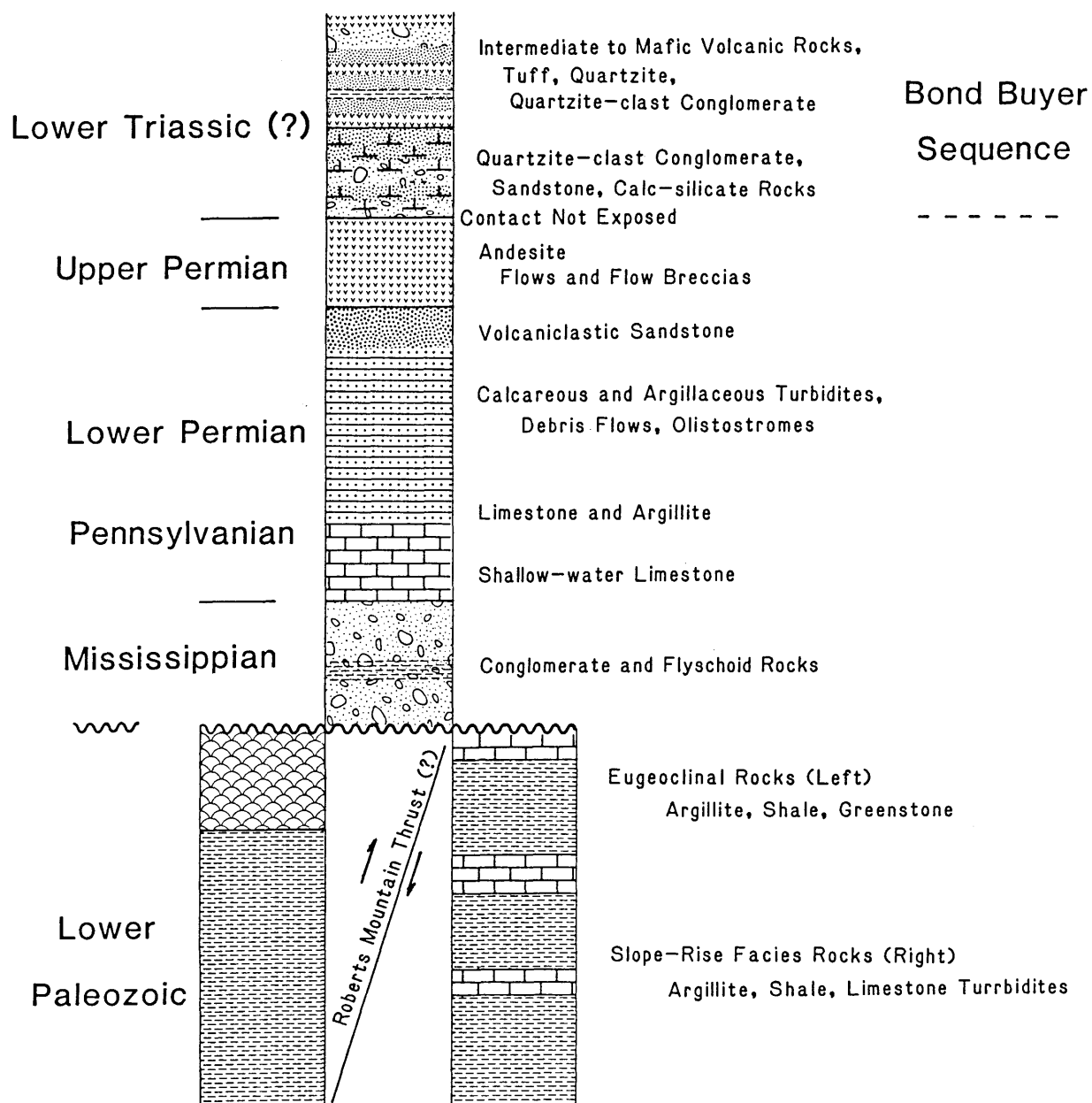
A thick sequence of sedimentary and volcanic rocks is exposed in the El Paso Mountains (Figure 4, 16). Cambrian to Devonian rocks were deposited in two distinct paleogeographic and tectonic settings:

- 1) eugeoclinal facies units comprising chert, argillite and siltstone,

greenstone, chert-pebble conglomerate, quartzite, and carbonate rocks probably deposited outboard of the continental margin; and
2) transitional-miogeoclinal facies units consisting of limestone, siltstone, chert, quartzite, slate, and greenstone which were probably deposited in a continental slope/rise environment (Carr and others, 1981, p. 15-16; M.D. Carr and others, 1984, p. 85, 88). The former are correlated with eugeoclinal rocks in the Roberts Mountain Allochthon of the Antler Belt, the latter with transitional-facies rocks of Nevada (Poole, 1974, p. 62; Carr and others, 1981, p. 17).

The eugeoclinal and transitional rocks were deformed and probably juxtaposed during the Devonian-Mississippian Antler Orogeny. Lower Mississippian argillite and chert-pebble conglomerate rest unconformably on the older deformed rocks (M.D. Carr and others, 1984, p. 90-91), and are overlain by Mississippian (?) argillite, quartzite, and turbidites. The next overlying unit consists of Pennsylvanian shallow-water limestone that is transitional upward into Pennsylvanian and Lower Permian deep-water turbidites. Permian rocks, in part, consist of distinctive late Wolfcampian to Guadalupian (?) mass-flow deposits which form a heterogeneous lower unit of argillite, conglomerate, olistostromes, and turbidites, and an upper unit of argillite and coarse limestone turbidites (M.D. Carr and others, 1984, p. 89). Lower Permian turbidites contain abundant resedimented shallow-water megafossils, indicating proximity to a shallow-water shelf source. The upper part of the Permian sequence contains volcanogenic debris, and it is conformably overlain by andesitic volcanic rocks. The age of the andesites is probably Upper Permian because they conformably overlie and are transitional into the uppermost Leonardian and Guadalupian (?) sedimentary rocks (M.D. Carr and others, 1984, p. 90),

Figure 16: El Paso Mountains composite section. Paleozoic strata generalized from several structural blocks in the area. From M.D. Carr and others (1984) and Christiansen (1961). Note, this is a composite section and the relations represented are not found in any single area.



and are infolded with Paleozoic rocks that are intruded by Late Permian plutonic rocks. This sequence was deformed and intruded by a series of Late Permian synkinematic to postkinematic granitic rocks. Ages of these plutonic rocks and style of deformation will be discussed below.

Probable Triassic rocks in the El Paso Mountains are named the Bond Buyer Sequence. The Bond Buyer Sequence consists of a distinctive section of calc-silicate rock, metaconglomerate, quartzite, and andesite that is exposed in the western part of the El Paso Mountains (Christiansen, 1961, p. 7). The Bond Buyer Sequence can be divided into two units each about 300 m thick: a lower unit of quartzite-pebble conglomerate interbedded with quartzite, feldspathic sandstone, and siltstone; and an upper unit of mafic and intermediate volcanic rocks locally interbedded with quartzite-pebble conglomerate and quartzite (Christiansen, 1961, p. 42-43). Clasts in the lower conglomerate include quartzite ranging from 1.5 to 45 cm in diameter, and the matrix consists of hornblende, quartz, albite, and epidote (indicating a calcareous protolith). Metavolcanic rocks in the upper unit consist of metatuffs, tuff breccias, and amphibolite. Calc-silicate rocks, which are derived from calcareous rocks, are interbedded in both units. The mineralogy of the calc-silicate rocks is essentially identical to the matrix material of the conglomerates, suggesting a similar origin. Conglomerate is interpreted to have been deposited in a limy-marine setting.

The Bond Buyer Sequence is unfossiliferous and is isolated from stratified rocks in the eastern part of the El Paso Mountains, so its age is difficult to determine. It is intruded by a granodiorite dated at 230 ± 7 and 229 ± 7 based on K/Ar analysis on biotite and hornblende, respectively, and diorite dated at 228 ± 7 based on K/Ar on hornblende (Cox

and Morton, 1982). M.D. Carr and others (1984, p. 90) tentatively assigned this unit to the Upper Permian based on correlation of volcanic rocks in the Bond Buyer with the andesites exposed to the east. Alternatively, I suggest that the Bond Buyer Sequence is Lower Triassic based on: 1) its lithologic similarity to Lower Triassic rocks within the Mojave Desert area; 2) its correlation with lithologically similar rocks of probable Triassic age in the Lane Mountain area (to be discussed below); and 3) its pre-230 Ma age based on intrusive relations with granodiorite.

Lane Mountain

McCulloh (1952, 1960, unpublished data) first mapped rocks in the Lane Mountain area; rocks in the Pilot Knob Valley are continuous along strike with those at Lane Mountain (Figure 4; Carr and others, 1981, Miller and Sutter, 1982; Carr, personal communication, 1983). M.D. Carr and F.G. Poole (Carr, personal communication, 1983) have reexamined these rocks and have made age assignments and stratigraphic correlations for many of the units in the area. My main source of data for Mesozoic rocks in this area is from an unpublished manuscript by McCulloh given to B.C. Burchfiel and M.D. Carr, and for Paleozoic rocks from Carr and others (1981) and personal communications from Carr, mainly during 1983. My attempts at restudy of this area were thwarted by gun-wielding prospectors holding patent claims to most of the Lane Mountain area. Because equivalent Paleozoic rocks from the El Paso Mountains have been described above, I concentrate on probable Triassic rocks in this section.

The Noble Well Formation of probable Triassic age (McCulloh, 1960, unpublished manuscript), consists of calc-silicate hornfels, meta-feldspathic sandstone, limestone-clast conglomerate, and chert-,

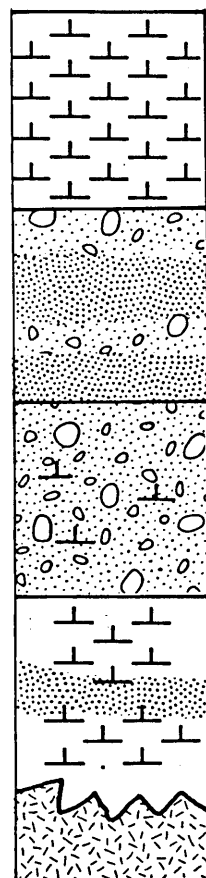
sandstone-, and marl-clast conglomerate (Figure 17). McCulloh (1952, p. 36) considers this unit to be more than 300 m thick, but deformation, intrusion, and metamorphism make its thickness uncertain. Calc-silicate hornfels and meta-feldspathic sandstone are the most common rock types in the Noble Well Formation. Feldspathic sandstone consists of quartz, plagioclase, microcline, epidote, muscovite, biotite, hornblende, and diopside. Calc-silicate rocks are typically dark green to gray and well stratified. McCulloh (1952, p. 42) considers marl and silty dolostone to be the protolith of the calc-silicate rock. Minor marble horizons are also present in the Noble Well Formation.

The age of the Noble Well Formation is not tightly constrained. It is exposed as pendants on the east side of the Larrea quartz diorite, which is interpreted as having been intruded at about 148 Ma (Miller and Sutter, 1982, p. 1204-1205), providing a minimum Late Jurassic age for these rocks. Fossil material recovered from this unit consists of a pelecypod of the family Cardiidae (McCulloh, unpublished data). This fossil is permissible of either a Triassic or Jurassic age assignment; McCulloh favored the former. Burchfiel and others (1980) considered these rocks to be equivalent to Lower Triassic rocks in the Soda Mountains and Victorville areas. I agree with this interpretation. Also, if the Noble Well Formation correlates with the Bond Buyer Sequence in the El Paso Mountains (Burchfiel and others, 1980), then their age is constrained as Triassic because of fossils in the Noble Well Formation but pre-230 Ma (age of plutonic rocks intruded into the Bond Buyer Sequence), effectively bracketing both the Noble Well Formation and the Bond Buyer Sequence as Lower Triassic.

Figure 17: Lane Mountain section. From McCulloh (1952, unpublished manuscript).

Lower
Triassic (?)

100 m



Calc-silicate Hornfels

Metasandstone and Conglomerate

Clasts in conglomerate comprise
sandstone, chert, and marl
(all now recrystallized)

Limestone clast Conglomerate

Arkosic Metasandstone and
Calc-silicate rock

Intruded

Noble Well
Formation

Summary of Northwestern Mojave Desert Rocks

Four important features stand out about the rocks in the El Paso Mountains and at Lane Mountain (northwest Mojave assemblage): 1) the presence of early Paleozoic eugeoclinal and transitional-facies rocks which probably correlate with the Roberts Mountain Allochthon and structurally lower strata; 2) Pennsylvanian and Permian turbidites and Lower Permian mass-flow deposits containing abundant shallow-water fossil material; 3) Upper Permian andesite; and 4) distinctive calc-silicate, conglomerate, and sandstone sequences of probable Early Triassic age. Eugeoclinal rocks which once belonged to the Roberts Mountain Allochthon of Nevada and eastern California are a unifying feature of the northwestern Mojave rocks, and point strongly to the out-of-place nature of these rocks in their present position. Permian turbidites and mass flow deposits are important in that similar rocks are present in miogeoclinal sections in the western Great Basin and may provide an important tie for the rocks of the northwestern Mojave region; this point will be emphasized below. Probable Lower Triassic rocks are important in that they provide a stratigraphic overlap sequence for the displaced rocks.

CHAPTER 4: Related Areas

Introduction

To determine the Late Permian and Early Triassic paleogeographic and tectonic settings of the southwestern United States, the details of stratigraphic sections beyond the Mojave Desert must be considered. In this chapter I present data from related stratigraphic sections of Paleozoic and Mesozoic rocks north, south, and east of the areas described in the last chapter to build a broader base for paleogeographic interpretations. Locations for sections described in this chapter are shown in Figure 4. I have visited and examined most of the areas described in California, western Nevada, southern Nevada, and southern Utah. Information pertaining to sections elsewhere comes from published descriptions. Descriptions will be fairly detailed for locations in western Nevada and California, but more general for other areas. After presentation of the data in this chapter, I will attempt to integrate these data into an interpretation for the Late Permian and Early Triassic paleogeography of the western United States, and hence attempt to constrain the timing and the processes involved in the truncation and the accompanying change in the trend of the Cordilleran continental margin and craton.

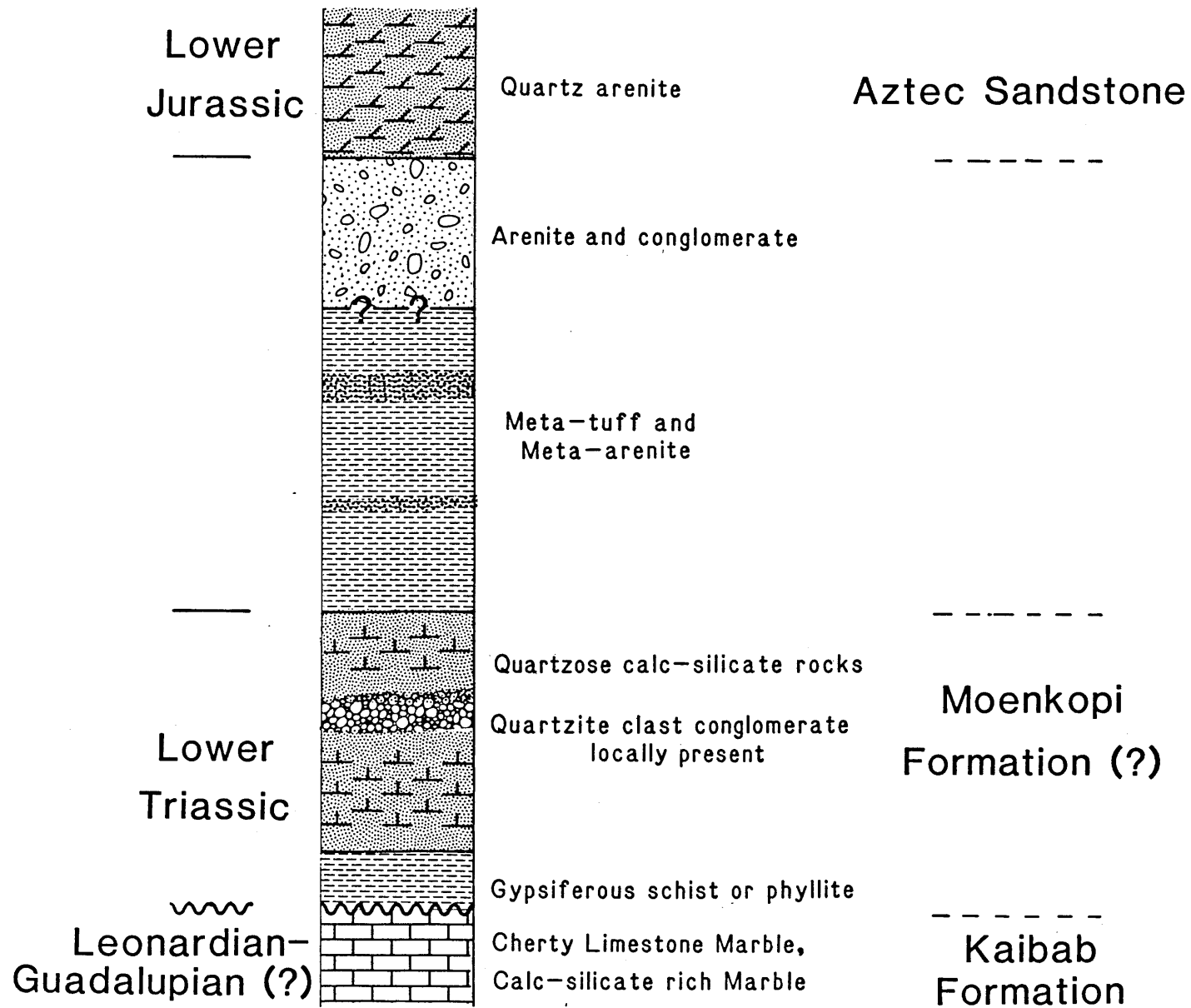
Southeastern California

Information on the stratigraphy of Paleozoic and Mesozoic sedimentary and metasedimentary rocks in southeastern California has increased greatly in the last five years. I present a generalized section for the area based on data from stratigraphic sections in the Arica Mountains (Baltz, 1982), Riverside Mountains (Lyle, 1982), Little Piute Mountains (Stone and

others, 1983), Big Maria Mountains (Hamilton, 1982), Little Maria Mountains (Emerson, 1982), and the Palen Mountains (LeVeque, 1982). The sections in the Little Maria, Arica, Riverside, and Little Piute Mountains were examined briefly during this study. C.M. Miller (1981) presented a summary of Mesozoic rocks in this area, and Stone and others (1983, 1984) and Brown (1984) have summarized the Paleozoic sequences. A generalized stratigraphic column for these areas is given in Figure 18.

Mesozoic rocks in southeastern California rest unconformably or paraconformably on the Kaibab Formation of Leonardian to Guadalupian (?) age (Figure 18). Gypsiferous schist and phyllite typically compose the basal member of the Mesozoic sequences. These gypsiferous rocks are overlain by sericitic quartzite containing quartz, microcline, tremolite, actinolite, and epidote, and had protoliths of calcarenite and calcareous siltstone rich in quartz. The composition of these rocks is similar to that of the sandy and silty limestone and calcareous siltstone of the Moenkopi Formation, whose main constituents are quartz grains and calcite cement (Stewart and others, 1972b, p. 60, 62; Cadigan, 1971, p. 22). The quartzose rocks often form the basal Mesozoic unit in many of these areas; gypsiferous rocks are commonly missing. C.M. Miller (1981) correlated the quartzose unit with the Lower Jurassic Aztec Sandstone, and Stone and others (1983) correlated it with Lower Triassic Moenkopi Formation. I favor the latter interpretation because of the lithologic and compositional similarity of the quartzose rocks to Lower Triassic rocks and differences with the Aztec Sandstone in the Mojave region. Interbedded with the quartzose rocks are beds of fine-grained sericite-epidote-mica schist and local beds and lenses of quartzite and quartzite-pebble conglomerate. Hamilton (1982, p. 11) reports clasts derived from Proterozoic granite and

Figure 18: Generalized stratigraphy of southeastern California. From Baltz (1982), Emerson (1982), LeVeque (1982), Lyle (1982), C.M. Miller (1981), Stone and others (1983)



various Paleozoic rocks in conglomerates in the Big Maria Mountains, indicating that there was some Permo-Triassic deformation in this area, although Precambrian rocks were probably not deeply buried.

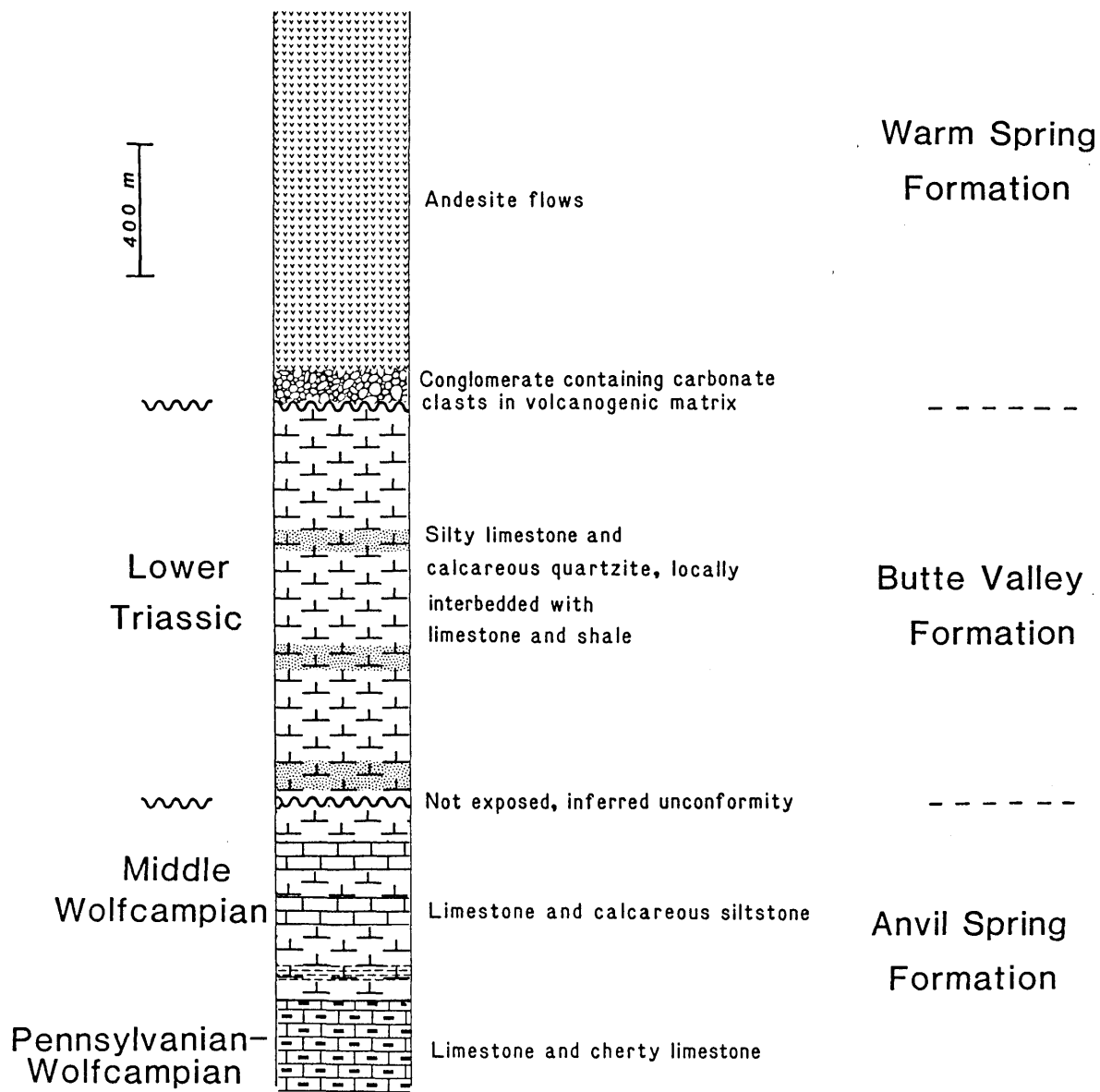
Rocks that overlie the calcareous rocks are variable in composition, and range from tuffaceous and conglomeratic sedimentary rocks to primarily volcanic flows. In the Palen Pass area, Triassic rocks are overlain by the Aztec Sandstone. This unit is the "true" Aztec, consisting of a vitreous feldspathic to quartzose arenite which has well developed large-scale (10 m) cross-stratification indicative of eolian origin (LeVeque, 1982). Thus, the quartz-rich rocks described above, and correlated with the Moenkopi Formation, are older than the Early Jurassic Aztec sandstone, and can best be assigned an Early Triassic age.

Death Valley Area

Lower Permian and Lower Triassic sedimentary rocks are exposed in the southern Death Valley area. Dated Permian and Triassic rocks are present in Butte Valley, and rocks inferred to be of this age are present in the Slate Range and Quail Mountains (Figure 4). The sequence is best preserved in Butte Valley.

In the Butte Valley area, Wolfcampian deep-water calcareous siltstones and limestones rest on Pennsylvanian to Wolfcampian shallower-water carbonates (Figure 19; Stone and Stevens, 1984a). All of these rocks were included by Johnson (1957) in the Anvil Spring Formation, although the lower part of this sequence may be best included in the Bird Spring Formation, and the upper part in Lower Permian turbidite sequences described by Stone and Stevens.

Figure 19: Butte Valley section. From Johnson (1957), this study, and Stone and Stevens (1984).



The Anvil Spring Formation is probably overlain unconformably or paraconformably by the Lower Triassic Butte Valley Formation although the contact is nowhere exposed. The Butte Valley Formation consists of thin to medium bedded, thinly laminated calc-silicate hornfels and quartzite. Isolated thin carbonate beds are also present. Quartz is the dominant detrital component, and diopside and tremolite occur as metamorphic porphyroblasts. The protolith of these rocks was most likely a calcareous quartz siltstone and sandstone locally rich in clays. Poorly preserved ammonites have been recovered from a shale unit near the top of the unit, and are probably Early Triassic (Johnson, 1957, p. 388). This age assignment is supported by the lithologic similarity of the Butte Valley Formation with Lower Triassic rocks in the Soda Mountains and in the Inyo Mountains (to be described below).

The Butte Valley Formation is overlain by volcanic and volcanoclastic rocks of the Warm Spring Formation (Johnson, 1957). Volcanic rocks of the Warm Spring Formation comprise more than 1300 m of andesite. The original thickness of these rocks is unknown since they are now unconformably overlain by Tertiary volcanic rocks. The contact is placed at the base of a conglomerate that contains carbonate clasts in a dominantly volcanoclastic matrix. The carbonate clasts appear to be derived mainly from the underlying Butte Valley and Anvil Spring Formations. The basal conglomerate varies in thickness from 3 to 30 m. Johnson interpreted the conglomerate unit to be a peperite of igneous origin, and the contact of the Warm Spring and Butte Valley Formations to be conformable, but transitional over about 100 m. This basal unit is actually a conglomerate of sedimentary origin and its contact with the Butte Valley Formation is an unconformity. The conglomerate unit is not present where the Warm Spring

Formation overlies the Anvil Spring Formation, but Wrucke (1966) reported that a thin quartzite unit is present locally. Johnson (1957, p. 385) considered the Triassic rocks (Butte Valley Formation and Warm Springs Formation) to form a northward-onlapping sequence, and he interpreted the Butte Valley and Warm Spring Formations to form a continuous northward onlap onto the Anvil Spring. The geologic relations suggest, however, that the Butte Valley Formation and underlying rocks were tilted and eroded prior to deposition of the conglomerate unit and extrusion of andesite of the Warm Spring Formation. Also, the interpretation of the base of the Warm Spring Formation as an unconformity renders Johnson's original age assignment of Middle Triassic for this unit uncertain; it can be dated only as post-Early Triassic (the age of the Butte Valley Formation) and pre-Late Jurassic (the age of the quartz monzonite that intrudes this area).

Recently Fowler (1982) and Moore (1976) have studied probable late Paleozoic and Mesozoic metasedimentary rocks exposed in the Ophir Mine area, on the western flank of the Slate Range (Figure 4). The metasedimentary rocks consist of layered calcareous hornfels with thin to thick marble horizons. Probable Permian pelmatozoan columns have been recovered from a sheared marble unit at the base of this section (Fowler, 1982, p. 15), but the entire age range of this sequence is unknown. Dating is complicated by multiple periods of folding and the intrusion of several generations of plutonic rocks. However, many of the lithologies present in this area and their general stratigraphic succession resemble the Lower Triassic Butte Valley Formation and probable Triassic rocks in the northernmost part of the Slate Range and farther to the north. Also, post-tectonic granitic rocks are of Middle to Late Jurassic age, so the entire sequence is pre-Middle Jurassic in age (probably pre-170 Ma; Folwer, 1982, p. 100).

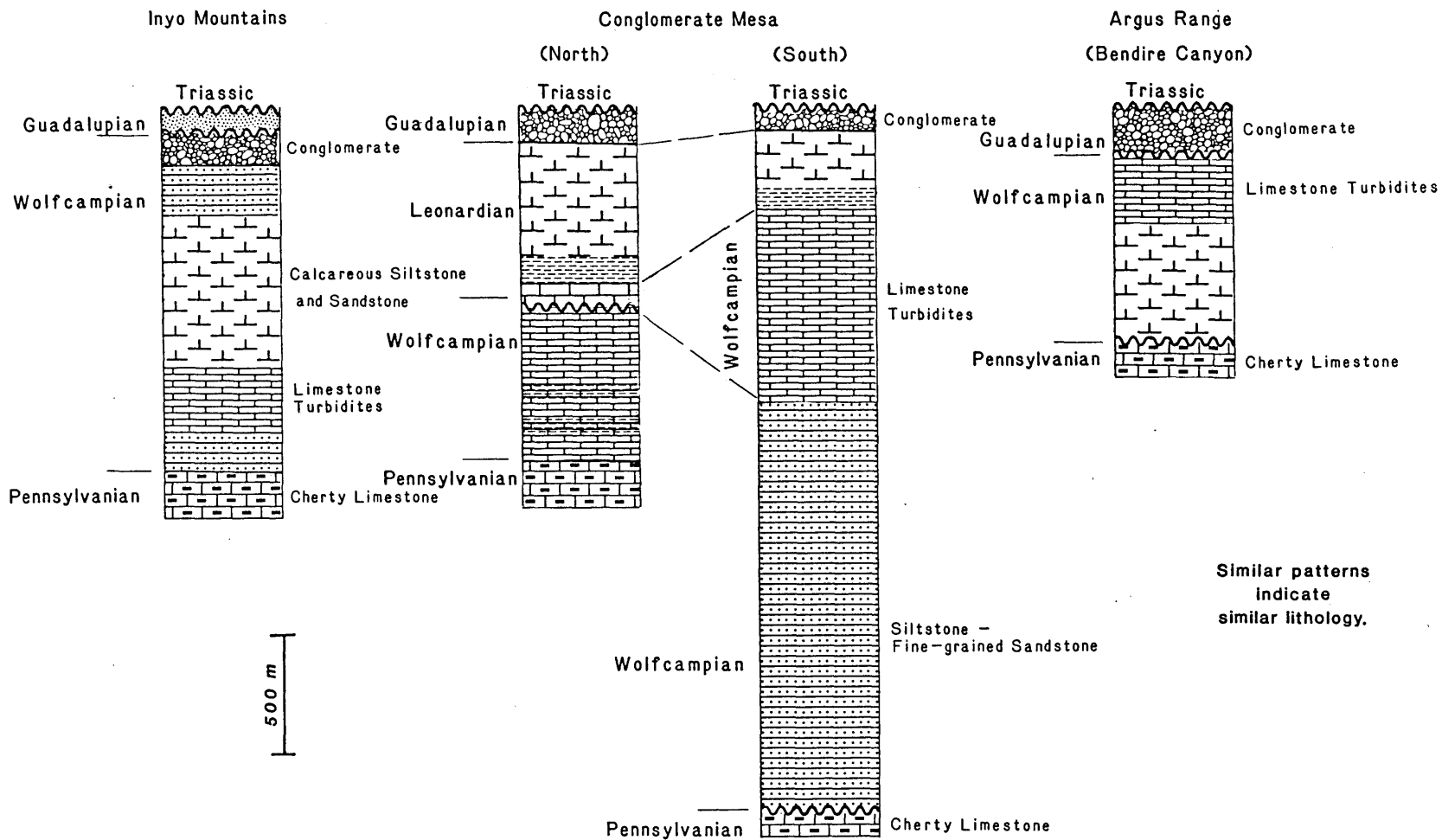
Lastly, structures in this area are probably equivalent to those in the southern Argus Range and the northern Slate Range that thrust metavolcanic and plutonic rocks above upper Paleozoic and Lower Triassic rocks, a relationship that supports a Triassic age assignment for the Ophir Mine rocks (Moore, 1976).

Muehlberger (1954) reported deformed metasedimentary and metavolcanic rocks in the Quail Mountains (Figure 4). The metasedimentary rocks consist of quartzite, phyllite, dolomitic marble, and mica schist. Metavolcanic rocks are primarily meta-andesite. Calc-silicate hornfels is also a common lithology, and may correlate with Lower Triassic rocks present around this area (B.C. Burchfiel, oral communication, 1983). However, the significance and exact age range of rocks in this area are very poorly known.

Argus Range and Darwin Hills

Lower Triassic and upper Paleozoic rocks are well exposed and well dated in the Argus Range and Darwin Hills area (Figure 4; Stone and Stevens, 1984a; Stone, personal communication, 1984; Lewis and others, 1983). In this area, unnamed middle to upper Wolfcampian turbidites rest paraconformably on Atokan (lower Middle Pennsylvanian) Bird Spring Formation (Figure 20; Stone and Stevens, 1984a). The Bird Spring Formation in this area was deposited in deeper water than that to the south; sedimentation occurred by quiet-water settling and debris flow mechanisms (Stone and Stevens, 1984a, p. 102). Middle to upper Wolfcampian rocks consist of calcareous mudstone and siltstone with interbedded limestone which were probably deposited by turbidity currents. Bioclastic and conglomeratic material in this unit was derived from a shallow-water shelf. The upper part of the sequence contains arkosic sandstone of uncertain

Figure 20: Composite Permian section in eastern California between Inyo Mountains and Argus Range. After Stone and Stevens (1984).



origin. These rocks are overlain unconformably by shallow-water limestone and conglomerate of Guadalupian age (Figure 20), and in some areas almost 2000 m of section is missing at the contact (Stone and Stevens, 1984a, p. 106).

Permian rocks are overlain by an unnamed sequence of Lower Triassic sedimentary rocks. These Lower Triassic rocks are well dated, and range in age from Griesbachian to Spathian, essentially spanning the entire Early Triassic (Lewis and others, 1983). The sequence comprises limestone, calcareous siltstone and sandstone, argillite, and conglomerate (Figure 21). A few meters of channelized conglomerate is present at its base and conglomerate is common in the lower part of the section. In the Darwin Hills and Darwin Canyon area, the upper and lower parts of this sequence were deposited under shallow-water conditions, probably in a nearshore environment. The middle part of this sequence, however, apparently contains deeper-water rocks: chert, radiolarian-rich argillite, and limestone are common. Some of these rocks were probably deposited by sediment gravity flows. The deeper-water rocks are primarily Dienarian in age, and coeval rocks in the surrounding area do not show such a deep-water aspect. South in the Argus Range, the Lower Triassic section contains dominantly shallow-marine, shelf-facies strata. Moore (1976) reported common plagioclase, albite, orthoclase, fine-grained diorite, and pumice fragments in sandstone units here, indicating that some volcanic and plutonic source was nearby. Also, feldspar is present as detrital fragments in silty limestones in the Darwin Hills.

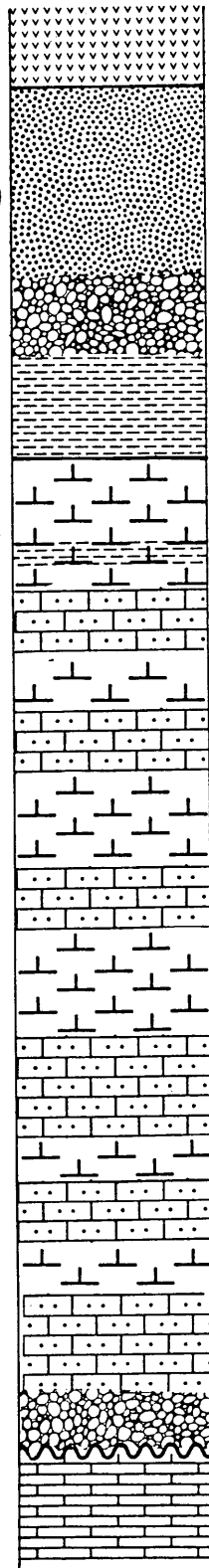
In the Argus and northern Slate Ranges, volcanic and volcanoclastic rocks are present. They are undated, but can be assigned a Middle (?) Triassic or younger age, because they are younger than the Lower Triassic

Figure 21: Triassic section in the Inyo Mountains. From Lewis and others (1983) and Osborne and others (1983).

Middle
Triassic (?)

Lower
Triassic

Lower-
Upper
Permian



Andesitic flows

Tuffaceous sandstone

Conglomerate with
limestone clasts

Shale and siltstone

Interbedded limestone,
silty limestone,
calcareous siltstone,
sandstone and shale

Basal Conglomerate

Limestone turbidites,
sandstone and conglomerate

100 m

rocks and intruded by plutons dated at 170 Ma. The original contact between the Lower Triassic rocks and the volcanic rocks is nowhere exposed. Further constraints on timing and sedimentologic processes will be discussed below.

Inyo Mountains

Permian and Triassic rocks are exposed in the southern Inyo Mountains. These rocks are especially important since the strata here, and in the Argus Range and Darwin Hills, provide vital information about the late Paleozoic paleogeography and tectonics in the western part of the miogeocline. Well studied sections are exposed at Cerro Gordo, Conglomerate Mesa, and Union Wash (Figure 4).

At Conglomerate Mesa, turbidites of Pennsylvanian and lower Wolfcampian age were apparently deposited in two separate basins (Figure 20). The different sequences were juxtaposed by thrust faulting and overlain by deep-water limestone and siltstone of middle to late Wolfcampian and Leonardian age (Stevens and Stone, 1985). These rocks are in turn overlain by shallow-marine and nonmarine shale, siltstone, sandstone, limestone, and conglomerate of late Leonardian to early Guadalupian (?) age (Stone and Stevens, 1984a, p. 105). The upper part of this sequence consists of a thick (150 m), Guadalupian chert-pebble conglomerate. The Permian rocks are overlain by an incomplete section of silty and sandy limestone of Early Triassic age. Schistose rock fragments are present in sandy beds of this unit.

In the Cerro Gordo and Union Wash areas of the Inyo Mountains, Triassic rocks overlie turbidites of Pennsylvanian to Leonardian age and conglomerate and shallow-water carbonate of Capitanian (upper Guadalupian)

age (Stone and Stevens, 1984a). These rocks range from Griesbachian to Spathian age so almost the entire Early Triassic is represented in this section. Conglomerate is present near the base of the section, and the middle part (dated as upper Dienarian (?), Smithian, and lower Spathian) at least in the Union Wash area, was probably deposited by turbidity currents in deep water (Lewis and others, 1983). The upper part of this section, deposited in shallow water, grades upward into Middle (?) Triassic terrestrial rocks containing volcanic detritus (Lewis and others, 1983; Osborne and others, 1983; Osborne, 1983, p. 9-10). The terrestrial sequence represents braided-stream and floodplain deposits, and detrital material was derived mainly from the west (Osborne and others, 1983; Osborne, 1983). The terrestrial rocks are transitional into overlying Middle (?) Triassic andesitic volcanic and volcanoclastic rocks. Unfortunately, the age of the volcanic rocks is only implied by their transitional contact with the underlying rocks of uppermost Spathian age. Neither the volcanics nor the underlying terrestrial sedimentary rocks have yielded fossils or been radiometrically dated.

The following is a summary of paleogeographic and tectonic changes in the Argus Range, Darwin area, and Inyo Mountains during Pennsylvanian to Triassic time. Information is based largely on a summary presented by Stone and Stevens (1984a, p. 110-114).

Deep-water sedimentary basins were created in Pennsylvanian and Permian time across former continental-shelf areas. The facies trends of the Mississippian and older shelf rocks were northeast, but creation of the deep-water basins established a new northwest trend. A complex pattern of topography was created in middle to late Wolfcampian time, and was accompanied locally by considerable subaerial erosion; as much as 1800 m of

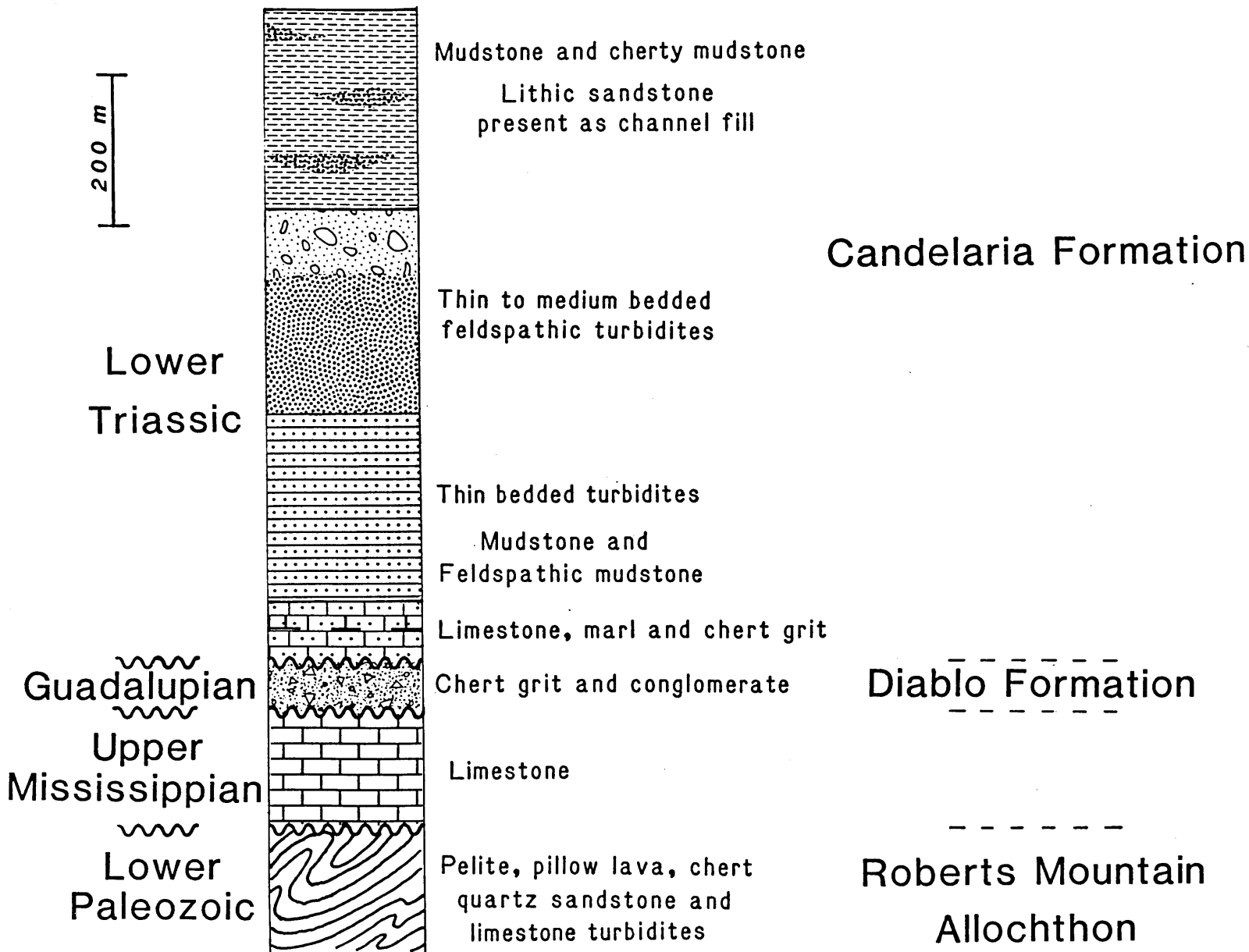
section was removed in the Inyo Mountains. Subaerial erosion led to the formation of pure quartz sand and chert detritus that was subsequently deposited as the latest Wolfcampian to Leonardian Reward Conglomerate. In most areas, however, shallow marine rocks of Capitanian age overlap the erosion surface. Subsidence resumed in Early Triassic time. Lower Triassic rocks record deposition in shallow water in the southern part, and deposition in shallow, deep, and then shallow environments in the northern part of the area. All these sequences are overlain by Middle (?) Triassic terrestrial sedimentary and volcanic rocks.

Mina-Western Nevada

Permian and Lower Triassic rocks are exposed in the Candelaria Hills, the Willow Spring area of the southern Toiyabe Range, and in the southern Toiyabe Range (Figure 4). Permian rocks belong to the Diablo Formation, and Lower Triassic rocks, to the Candelaria Formation (Figure 22). These rocks rest unconformably on deformed lower Paleozoic eugeoclinal rocks of the Roberts Mountain Allochthon and locally on Upper Mississippian limestone and are structurally overlain by an allochthon composed of serpentinite, and volcanic and sedimentary rocks (Speed, 1984; Poole and Wardlaw, 1978; Speed and others, 1977).

The Diablo Formation consists of 10 to 60 m of conglomerate and calcareous sandstone; terrigenous sand-size material and clasts in conglomerate include quartz, argillite, and chert. Megafossils from the Diablo Formation yield late Wolfcampian and Guadalupian ages (Speed, 1984, p. 75). Poole and Wardlaw (1978, p. 274-275) presented fossil evidence to show that the deposition of the Diablo Formation was diachronous. They dated the Diablo Formation as Leonardian in the Toiyabe Range, and lower

Figure 22: Section in the Candelaria Hills, near Mina, western Nevada.
From Speed (1984) and Poole and Wardlaw (1978).



Guadalupian in the Candelaria area. The Diablo Formation was deposited in a nonmarine to shallow-marine setting (Poole and Wardlaw, 1978, p. 275; Speed and others, 1977, p. 303). Deep-water rocks of various ages and clast compositions were assigned to the Diablo Formation or called Diablo rocks by Speed and others (1977, p. 307), but usage of the name Diablo or Diablo Formation should probably be restricted to shallow-water rocks of Leonardian and Guadalupian age (Poole and Wardlaw, 1978, p. 272).

The Diablo Formation is overlain by the Lower Triassic Candelaria Formation. The basal unit of the Candelaria consists of marl and limestone of Griesbachian and Dienarian age, which was metamorphosed to marble and calc-silicate hornfels. This unit was probably deposited in an outer-shelf environment based on the interpretation of sedimentary structures (Speed, 1984). The basal unit of the Candelaria Formation is overlain by volcanoclastic sandstone and conglomerate that were probably deposited in relatively deep water, possibly on a submarine fan by turbidity currents (Speed, 1984). In the Toquima Range, clasts of serpentinite are present in the volcanoclastic sediments (Poole and Wardlaw, 1978, p. 275). The uppermost unit contains mudstone, cherty mudstone, and sandstone of early Spathian age. The top of the Candelaria Formation is everywhere faulted against serpentinite melange and Early Triassic sedimentary rocks of unknown affinity.

The general structural and sedimentological evolution of the Mina area led Speed (1979, 1984) to suggest that the Diablo and Candelaria Formations record the approach and collision of an island arc with North America in Early Triassic time. The island arc, called Sonomia by Speed (1979), is now dismembered and poorly exposed, and only the volcanic carapace of the arc can be recognized. Volcanic rocks of the Black Dyke Formation and

volcaniclastic rocks of the Mina Formation form Sonomia in the Mina area; other Sonomian rocks are present in scattered exposures around northwestern Nevada. The volcanic rocks assigned to Sonomia by Speed have been radiometrically dated as Late Mississippian to Late Permian (Speed, 1984, p. 73) and have $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios of 0.704 to 0.7055 (Speed, 1979, p. 282), i.e., in the range of values found for island arcs.

Chemical composition and radiometric ages of plagioclase grains are identical among the Black Dyke, Mina, and Candelaria Formations. Speed (personal communication, 1984) interprets this relationship, along with the data reviewed above, to mean that the deepening of the Candelaria basin was caused by the encroachment of the Sonomia arc, which is represented by the Black Dyke and Mina Formations, and that erosion of volcanic material from the arc was the source of the volcaniclastic rocks in the Candelaria Formation. The setting of the Candelaria Formation would be analogous to a foredeep in this model. Collision would have occurred at the end of Candelaria deposition, at the end of the Early Triassic. Serpentinite melange and deformed Paleozoic and Lower Triassic rocks between the Candelaria Formation and Sonomia represents an accretionary complex formed in front of the encroaching arc.

In summary, sequences in the Mina area record complexly changing tectonic and paleogeographic settings. However, the lower part of the Candelaria Formation is remarkably similar lithologically to Early Triassic rocks to the south in the Inyo Mountains. The importance of this similarity and implications of the ages of rocks in these areas will be discussed in detail in the following chapters.

Southeastern Sierran Pendants

Sections of Paleozoic rocks up to 10,000 m thick are exposed in the Mount Morrison, Bishop Creek, and Pine Creek roof pendants of the eastern Sierra Nevada (Figure 4). The stratigraphy of lower Paleozoic rocks in these pendants is well known, and correlates well with that of rocks to the east in the White and Inyo Mountains, and the Silver Peak area of Nevada (Figure 4; Moore and Foster, 1980; Rinehart and Ross, 1964, p. 28). The stratigraphy of the upper Paleozoic rocks is not as well understood. About 2500 m of Pennsylvanian and Permian (?) siliceous hornfels and marble are exposed at Mount Morrison (Rinehart and Ross, 1964); siliceous hornfels in the Pine Creek Pendant is probably correlative with these rocks (Bateman, 1965). Lower Paleozoic rocks are transitional - continental slope in character; the paleogeographic and tectonic affinities of the upper Paleozoic rocks are unknown. The two rock groups are always in fault contact.

Mesozoic sequences comprise volcanic and volcanoclastic rocks that rest unconformably on the Paleozoic sedimentary sections between the Ritter Range and Mount Morrison area and the Pine Creek Pendant to the south (Figure 4; Bateman, 1965; Rinehart and others, 1959; Brook and others, 1974). The volcanic rocks are locally interbedded with marine sedimentary rocks which contain Early Jurassic fossils. Many radiometric dates have been reported for the lower part of these sequences: 256 ± 26 Ma (Rb/Sr whole rock; Kistler, 1966); 237 ± 11 Ma (Rb/Sr whole rock; Kistler, 1981); and 186-215 Ma (U/Pb zircon; Fiske and Tobish, 1978, p. 120). Hence, the age of the base of this sequence is not well constrained, and the dates given by Kistler (1966, 1981) are not true isochrons, but rather are errorchrons. However, the dates reported above are consistent with the

interpretation that these rocks, at least in part, are probably Triassic. The upper part of the volcanic sequence, above the Lower Jurassic marine rocks, has been dated as 153 and 158 Ma (U/Pb zircon, Fiske and Tobish, 1978) and as 185 ± 6 Ma (Rb/Sr whole rock, Kistler and Swanson, 1981). Thus, the section of volcanic rocks can be assigned a Triassic and Jurassic age based on both absolute and biostratigraphic data.

Saddlebag Lake Pendant

Lower Paleozoic and Mesozoic rocks are exposed in the Saddlebag Lake Pendant (Figure 4). Brook (1977) mapped this area and identified many of the major contacts within the Paleozoic and Mesozoic rocks (although he assigned portions of the Mesozoic sequence to the Permian). Schweickert and Lahren (1984) have suggested new correlations for rocks at Saddlebag Lake with rocks of known age and paleogeographic affinities to the east. Lower Paleozoic rocks consist of chert, slate, quartzite, basalt, and marble of Ordovician and Silurian (?) age. Schweickert and Lahren correlate these rocks with the Ordovician to Devonian Palmetto Formation exposed at Miller Mountain (the southern continuation of the Candelaria Hills) in western Nevada, which is part of the Roberts Mountain Allochthon.

Lower Paleozoic rocks are unconformably overlain by 1000 to 2000 m of quartzofeldspathic siltstone and sandstone which Schweickert and Lahren (1984) correlate with the Lower Triassic Candelaria Formation of the Mina area, and by a heterogeneous mixture of volcanic and volcanoclastic rocks. The lower part of the volcanic rocks has been dated at 222 ± 7 Ma (U/Pb zircon; R.A. Schweickert, oral comm., 1985).

The tectonic and paleogeographic affinities of these rocks are very important. If the Saddlebag Lake sequence does correlate with rocks in the

Mina area, then a simple westward continuation of the Antler belt into this area is implied, and Paleozoic paleogeographic belts and trends are probably continuous to the west into the pendants in the eastern part of the Sierra Nevada Batholith. Also, there are probable Upper Paleozoic (?) rocks at Saddlebag Lake that may correlate with allochthonous Upper Paleozoic rocks at Mina (Schweikert and Lahren, 1984; R.A. Schweickert, oral communication, 1985).

White Mountains

Probable Triassic metasedimentary and metavolcanic rocks are exposed on the west side of the White Mountains (Crowder and Ross, 1972; Dunne and others, 1978). The section in this area is structurally disrupted, and neither the base nor the top is exposed. The section is composed of a lower metasedimentary and metavolcaniclastic unit, a middle unit of mafic volcanic flows, and an upper mixed siliceous and mafic volcanic unit. The lower metasedimentary unit is of greatest interest in this study. It contains slate, phyllite, metasandstone, marble, and conglomerate with clasts of volcanic rocks, quartz, and limestone. These rocks were probably deposited in an alluvial environment, and sedimentary clasts were derived from Paleozoic and upper Precambrian rocks to the south (Fates and Hanson, 1985). The age of the lower metasedimentary unit and overlying metavolcanic rocks is not well constrained: the presence of volcanic rocks suggests a Mesozoic rather than Paleozoic age, and the rocks are intruded by the Middle Jurassic Mount Barcroft Pluton (Crowder and others, 1973; Dunne and others, 1978), which has yielded an age of 165 Ma (U/Pb zircon; D.G. Fates, personal communication, 1985). The metasedimentary and metavolcanic rocks were deformed prior to intrusion of the Barcroft pluton

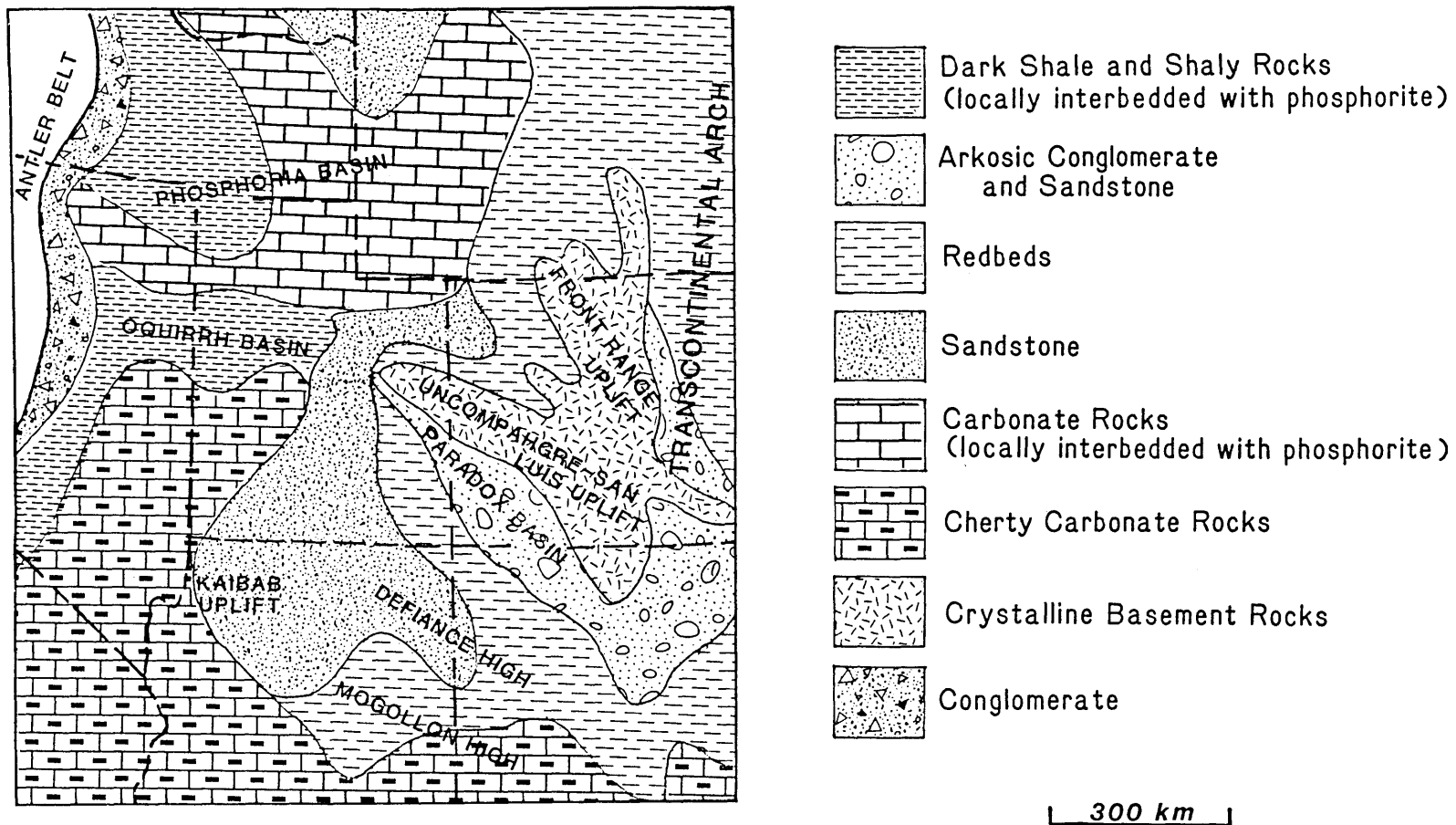
(Hanson and Fates, 1985). The metavolcanic rocks do not resemble Mesozoic sequences to the south in the Inyo Mountains, but do resemble siliceous volcanic rocks in the Ritter Range area to the west (Figure 4). Thus, I tentatively assign these rocks a Triassic age, but the exact age and significance of this section remains uncertain.

Eastern Nevada, Utah, and Arizona

Because of the extremely large area of good exposure of Paleozoic and Mesozoic rocks in eastern Nevada, Utah, and Arizona, an entire thesis could be devoted to describing the late Paleozoic and early Mesozoic sections in this area alone; only a brief summary of late Paleozoic and early Mesozoic paleogeography and tectonics of this area is given here. This approach is reasonable because our understanding of the structure and stratigraphy of this area is good compared to the areas discussed above. The main sources of data and interpretations of the late Paleozoic rocks in this summary are review articles by Peterson (1980) and Blakey (1980).

The Ancestral Rocky Mountains were created by uplifts of crystalline basement rocks in late Paleozoic time, and their presence greatly influenced patterns of sedimentation and sediment source areas in the miogeocline. The Uncompahgre-San Luis and Front Range uplifts were the principal basement highs during the Permian (Figure 23). Despite tectonic activity in late Paleozoic time, the general trend of the miogeocline and craton edge did not change because the uplifts occurred mainly along the trend of the long established Transcontinental Arch, the original eastern boundary of the miogeocline. The miogeocline was bounded to the west by remnants of the Antler Highland, which continued to shed debris eastward. Carbonate and shale were the principal sediment types deposited into the

Figure 23: Generalized Permian lithofacies of the west-central United States, after Peterson (1980). This figure shows the positions of the main uplifts and topographically positive areas.



Generalized Permian Lithofacies

central part of the basin. In southern Nevada, Permian deposits are represented by shallow-water carbonates of the Bird Spring and Kaibab Formations described above for the Spring Mountains.

The Permian marine rocks of the miogeocline grade eastward into shallow-marine and nonmarine cratonal sections in Arizona and southeastern California consisting of shallow-water carbonates rich in biogenic material, interbedded with eolian sandstone and various other nonmarine clastic rocks. Major transgressive-regressive pulses during the Permian are reflected in large and rapid shifts in the boundary between marine and nonmarine deposition. The topographic relief of this area was very low, and served to amplify facies shifts caused by small changes in sea level.

A major regression in Late Permian time caused deposition to cease in the miogeocline (Peterson, 1980). The axis of the miogeocline probably shifted to the north from southern Nevada and California into southern Idaho, because rocks in the Permian sequences young in this direction; and rocks to the north were deposited in slightly deeper and quieter water than those to the south. However, some erosion of Permian rocks probably occurred in late Permian and earliest Triassic time as the sea retreated, and may enhance this apparent northward younging. Upper Permian strata are missing in Arizona, and were probably never deposited.

The Antler Highland was still present in Permian time, but its relief was minor compared to that during Mississippian time. Miogeoclinal rocks become shallower water in character and conglomeratic toward and within the highland. Also, many unconformities are present in the Antler Overlap sequence. In this and following sections I use the term Antler Highland and Antler belt to describe that area of central Nevada that remained high throughout late Paleozoic time. Only part of this area is underlain by

lower Paleozoic eugeoclinal rocks of the Roberts Mountains Allochthon. However, rocks to the east of the Roberts Mountains Allochthon are also shallow water in character throughout upper Paleozoic time. Hence, the area of east-central Nevada where Permian and Lower Triassic rocks shoal to the west will be included in the area covered by the term Antler Highland. This area includes all that region underlain by strata that shoal onto the Antler Highland even though they may not lie directly on the Roberts Mountain Allochthon or its cover rocks.

In summary, Late Permian deposits were bounded by two highlands: on the west by the Antler belt and on the east by the Transcontinental Arch. The Transcontinental Arch, however, was punctuated by several large positive areas created by uplifts of crystalline basement rocks during the formation of the late Paleozoic Ancestral Rocky Mountains. Hence, Late Permian paleogeography followed patterns similar to those established in Middle Paleozoic time.



Patterns of sedimentation in the miogeocline and onto the craton during Early Triassic time changed little from those of Late Permian, especially in Arizona and Utah (Figure 24). In the east, the Uncompahgre-San Luis, Defiance, and Mogollon uplifts were still present and provided major sources of clastic material for the Moenkopi Formation (Peterson, 1980; Stewart and others, 1972b, p. 77-81). Thus, the eastern edge of Early Triassic deposits was similar to that for Late Permian deposits. Also, just as Late Permian facies are regressive to the north, Triassic facies are transgressive to the south along the miogeocline axis, and the base of the Triassic rocks become younger from north to south.

The western edge of the Early Triassic depositional basin is not well defined. The presence of a western source region in southern Nevada is



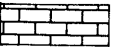

Figure 24: Generalized Early Triassic lithofacies of the west-central United States. After Stewart and others (1972b), Carr and Paul (1983), and Collinson and others (1978). The connection of the Antler Highland with emergent area in southern Nevada is not constrained at present.



Emergent Areas

-  Precambrian Crystalline Basement Rocks
-  Permian Cherty Carbonates

Lower Triassic Rocks

-  Conglomerate
-  Redbeds, Fluvial Deposits
-  Marine Limestone, Siltstone, Sandstone, and Gypsum
-  Basinal Siliceous Deposits

Generalized Early Triassic Lithofacies

suggested by chert-pebble conglomerates and shallowing of facies in the Moenkopi Formation in the Spring Mountains; clastic material in this unit is derived from the west, and the Moenkopi Formation rests on progressively older Permian rocks to the west. However, because the Virgin Limestone Member of the Moenkopi Formation is present in the Providence Mountains of southeastern California, a connected seaway must have existed from Utah into California. Collinson and others (1976) noted that Lower Triassic rocks onlap older strata to the west in central Nevada, and reported that conglomerate and sandstone of local clast derivation occur to the west, in the area of Currie, Nevada (Figure 4). Collinson and Hasenmueller (1978) suggested that a highland might have extended from central Nevada into southern Nevada and acted as a western source for the Moenkopi (Figure 24). The northern part of this highland would correspond to the Antler belt in the sense used in this thesis, and the southern would have been created in Permo-Triassic time. However, the continuity of this highland was questioned by Carr and Paull (1983, p. 48), who suggested that the gravels that form the conglomerate in the Currie area were shed northward from east-west-trending structures rather than eastward from north-south-trending structures. Carr and Paull also pointed out that Early Triassic facies and faunal patterns in conodont populations tend to strike straight into the Antler Belt. (This may also be true of trends of isopachs for Late Permian rocks.) A major problem in interpreting facies and depositional patterns is that owing to the lack of continuous exposure. We cannot directly determine whether there was a continuous belt of deposition in Early Triassic time between the Currie area and the Spring Mountains.

The confusion concerning the role of a western highland is resolved if we interpret the Antler highland to be subducted during Early Triassic time, and thus incapable of producing or supplying large quantities of terrigenous material into the Early Triassic basin. Also, a subducted highland would have little effect on facies patterns. This interpretation is supported by relations in the Spring Mountains in southern Nevada, where facies patterns are affected only very near the proposed western source region, and show little modification immediately to the east. As Triassic deposition transgressed southward in the remnant miogeocline, facies belts were well developed along the highlands to the east, but lap onto the subducted Antler highland to the west. We should not expect symmetric facies patterns east and west since possible source rocks in central Nevada (Permian carbonates and other calcareous Antler Highland rocks) are unlike those in Utah (crystalline basement rocks). Thus, I adopt the interpretation that a highland existed in central Nevada along the older Antler trend, but departed from this trend to reach the area of the Spring Mountains. This interpretation could change radically, however, when more data are collected.

Sonoma Orogeny

Lastly, we need to consider Permo-Triassic events in western Nevada that bear on the interpretations of paleogeography and tectonics. During Late Permian and Early Triassic time, upper Paleozoic oceanic rocks of the Havallah sequence, deposited to the west of the Antler belt, were deformed during the Sonoma Orogeny. The Sonoma Orogeny is dated by the unconformable overlap of Early Triassic (and older?) Koipato Formation on top of deformed rocks of the Pennsylvanian and Permian Havallah sequence

which forms the Golconda Allochthon (Silberling and Roberts, 1962, p. 36). The Havallah rocks were thrust eastward onto the western margin of North America, and now lie above the Antler belt and its upper Paleozoic cover, but were not transported as far east as the Roberts Mountain Allochthon. We do not know, however, if the Havallah rocks were thrust into their present position in Permo-Triassic time, or if significant transport took place in later Mesozoic time. The Havallah sequence consists of chert, tholeiitic greenstone of oceanic type, and turbidites, and was probably deposited in an oceanic basin that was marginal to the miogeocline and Antler Highland (Miller and others, 1984). The rocks in the main part of the Havallah sequence in central Nevada are as young as late Early Permian; in the Mina area, however, rocks equivalent to the Havallah sequence may be as young as early Triassic. In the type area of the Sonoma Orogeny (China Mountain; Ferguson and others, 1952) the upper limit of deformation is constrained as Upper Permian or lowest Triassic (pre-Kaipato Formation), whereas the upper limit of deformation in the Mina area may be somewhat younger (pre-Middle Triassic). Alternatively, Snyder and Brueckner (1983) suggested that deformation of the Havallah rocks took place in an accretionary-prism setting, and was continuously active during late Paleozoic time, and was essentially syndepositional; overlap of the oceanic sequence occurred when deformation ceased. They base this interpretation on details of deformational fabric development in these rocks.

One tectonic interpretation of the Sonoma Orogeny is that the late Paleozoic Havallah rocks were emplaced as the Golconda Allochthon onto the edge of the continent (Silberling and Roberts, 1962, p. 51; Roberts, 1968). This event would be analogous to the emplacement of the Roberts Mountain Allochthon during Antler Orogeny. In almost all models presented for the

Sonoma event, the deformation in the Havallah rocks is interpreted to have occurred in an accretionary prism that was thrust onto the continental edge. Importantly, the emplacement of this allochthon onto the craton produced no noticeable effects on patterns of sedimentation: there are no Triassic rocks analogous to the Antler foredeep in Nevada, with the possible exception of the Candelaria Formation in the Mina area. Many authors (i.e., Collinson and others, 1976; Collinson and Hasenmueller, 1978; and others) attribute renewed uplift of the Antler belt in Permo-Triassic time to the Sonoma Orogeny. This uplift could have been caused by an outer arch high created on the order of 100 to 400 km in front of an encroaching arc (Dickinson and Seely, 1979). Such a mechanism has been proposed for the Antler Orogeny (Dickinson and others, 1983, p. 502) and the Sonoma Orogeny around Mina (Speed, 1984). Alternatively, uplift may be entirely unrelated to Sonoma activity. If the Golconda Allochthon was emplaced on the continental edge during Permo-Triassic time, the continentward displacement was probably small because evidence of foredeep deposits is lacking.

Structural and stratigraphic relations in the Mina area have been suggested to be the best for recording the nature and timing of the Sonoma Orogeny. Speed (1978, 1984) attributed emplacement of the Golconda Allochthon to collision of an island arc, Sonomia, with the craton. In the Mina area, rocks correlated with the Golconda Allochthon (and Havallah sequence) rest structurally above serpentinite melange thrust onto the Lower Triassic Candelaria Formation, and structurally below Upper Permian andesite of the Black Dyke Formation and volcanoclastic rocks of the Mina Formation, which are interpreted to be part of Sonomia. Speed interprets these relations to indicate that the Sonomian arc shed debris into the

Candelaria basin during encroachment and before final collision. The ocean that was closed is represented by the structurally intervening Golconda rocks and(?) serpentinite melange. A late Early Triassic age for final collision and closing of the ocean basin is implied in this model because of 1) the Early Triassic age of volcanoclastic rocks in the Candelaria Formation, supposedly derived from Sonomia; and 2) the Early Triassic age of the youngest rocks in the Golconda Allochthon in the Mina area. A major problem with this reconstruction is that debris from the Sonomian arc would have had to bypass the Havallah basin to be deposited in the Candelaria basin, at the same time that Havallah rocks were being deposited. A foredeep was not formed in central Nevada, presumably because the collision there was not as severe as in the Mina area.

The significance of the unconformably overlapping siliceous volcanic rocks of the Koipato Formation in this tectonic framework is unclear. These volcanics may have been extruded as the last gasp of the Sonomian arc as it contacted North America. Alternatively, they could represent rift-related volcanics in some complicated back-arc setting. They also may have been extruded on the eastern flank of the collided arc if subduction flipped to its west side. Upper Spathian platform carbonates are deposited on the Koipato (Silberling and Wallace, 1969). How, or even if, Early Triassic rocks in the miogeocline connected across the Antler highland with shelf-facies rocks in west central Nevada is unknown. Triassic shelf rocks in west-central Nevada rest on the Havallah Sequence and the Koipato Formation (Speed, 1978, p. 255). However, we do not know whether the Golconda rocks were connected with North America at this latitude in Early Triassic time. Interestingly, shallow-water sedimentation started in this western platform area about the time it ceased in the miogeocline to the

east. Lower Triassic rocks are not present on the main part of the Antler Highland, that is, the part underlain by the Roberts Mountain Allochthon, and Koipato and overlying rocks rest only on the Havallah Sequence. Thus, no unified paleogeographic framework can be presented for Early Triassic time in Nevada, mainly owing to the the lack of continuous exposure and structural complexity of Lower Triassic rocks.

In summary, the Havallah sequence was deformed in Late Permian or Early Triassic time, before the extrusion of the Koipato Formation. The Havallah was probably emplaced partway onto the continental edge as the Golconda Allochthon. However, there is no demonstrable Early Triassic sedimentary overlap of both the Golconda Allochthon and North America, so its final emplacement could be as young as Jurassic. Also, the orogeny may be diachronous: younger in the south near Mina, and older to the north.

CHAPTER 5: Permian and Triassic Paleogeography and Tectonic Settings

Introduction

In this chapter I present an interpretation for the paleogeography and tectonic setting of the Mojave Desert and surrounding areas in Late Permian and Early Triassic time. I include details of paleogeography as far north as southern Idaho and as far south as southern Arizona. Late Permian and Early Triassic paleogeography are emphasized, but earlier and later times must also be considered to obtain the clearest possible picture of Permo-Triassic paleogeography and tectonic setting.

Late Permian Paleogeography

The Late Permian paleogeography of eastern Nevada, Utah, and Arizona was little changed from that established during late Paleozoic time, with respect to both the Antler belt and the Ancestral Rocky Mountains. Rocks of Uchoan age are very scarce and poorly developed, and the youngest Permian rocks exposed in western Utah and eastern Nevada are of Guadalupian age. Uchoan age rocks are known only from west Texas and New Mexico and are poorly developed worldwide because of the major Late Permian regression. Based on the similarities of Guadalupian and Early Triassic paleogeographic settings, however, a reasonably reliable picture of Late Permian paleogeography and tectonic setting as a whole can be made without fear of missing major intervening tectonic events in latest Permian time. A summary map of Upper Permian rocks and their paleogeographic settings is given in Plate 1.

A restricted basin existed in southern Idaho, northwestern Utah, and northeastern Nevada (Morgan, 1980). Rocks deposited in this basin are cherty and phosphatic shales and phosphorite that grade eastward into

carbonates and bedded evaporites and redbeds. (This is the classic Phosphoria Basin and its transition onto the craton.) Shallow-marine conditions followed, and these deeper-water rocks are overlain by fossiliferous carbonates. Rocks of the Phosphoria Basin grade southward into shallow-water carbonates of the Kaibab Formation in southern Nevada and Arizona. The depositional system consisted of several local highs and lows, but overall followed the trend of the late Paleozoic miogeocline.

In southern Nevada, southern Utah, and northwestern Arizona, a thick sequence of Lower Permian carbonate and terrigenous sedimentary rocks is exposed. Upper Permian rocks, however, are rather thin and poorly developed. In most areas, the youngest Permian rocks exposed belong to the Kaibab Formation of Leonardian and lower Guadalupian age. Farther to the southwest, in the Providence and New York Mountains in California, the youngest rocks present below Lower Triassic rocks belong to the Lower Permian Bird Spring Formation. Whether the Kaibab Formation or other Upper Permian rocks were ever deposited in this area is unknown. The central and western parts of the Mojave Desert were probably emergent during Late Permian time, so nondeposition of Upper Permian strata in the New York and Providence Mountains is likely.

Thus, the southwestward extent of Upper Permian deposition along the miogeocline axis is uncertain. The observed top of the Permian rocks is always marked by an unconformity or paraconformity, and the amount of time and strata missing at the contact is unknown. Also, the extent of Upper Permian rocks in south-central Nevada is unknown because no rocks of this age are present. Specifically, rocks younger than Pennsylvanian and older than Cretaceous are missing north of the Spring Mountains in the Nevada Test Site and surrounding areas. The Kaibab Formation is progressively

bevelled northwestward across the Spring Mountains (Bissel, 1974, p. 92). This suggests that Upper Permian rocks to the north of the Spring Mountains are missing because of post-Guadalupian erosion rather than nondeposition. Rock units that are exposed in southeastern California and Arizona follow paleogeographic trends that differ little from the older Paleozoic miogeoclinal trends.

Stratified rocks of Permian age are poorly studied to the west of the Soda Mountains and Devils Playground area (Plate 1). Pennsylvanian and Permian strata are not recognized in the Victorville area. However, the Lower Triassic Fairview Valley Formation contains clasts of Wolfcampian limestone in presumably locally derived conglomerate (Bowen, 1954, p. 41), so Lower Permian carbonate rocks were probably present in the Victorville area. Lower Permian rocks are present in the San Bernardino Mountains, and probably correlate with the Bird Spring Formation (Stewart and Poole, 1975, p. 209; Brown, 1984a). No strata equivalent to units younger than the Bird Spring Formation are present in either of these areas; since the Bird Spring is only as young as Leonardian, Upper Permian rocks are missing in the western Mojave Desert.

Cratonal-transitional rocks in the western Mojave Desert were deformed, metamorphosed, and intruded prior to 242 Ma (age of the monzonite in the Victorville area) and prior to deposition of the Lower Triassic Fairview Valley Formation. Tectonism is probably post-Wolfcampian because clasts of this age are present in Lower Triassic conglomerate in this area (a similar conclusion was reached by E.L. Miller, 1981, p. 587, 591).

C.F. Miller (1978) interpreted plutons emplaced in Permo-Triassic time to be related to subduction. E.L. Miller (1981) interpreted deformation, plutonism, and metamorphism in the Victorville area to have occurred in a

magmatic arc setting. Hence, I place the western part of the Mojave Desert area in an Andean-arc setting during Late Permian time. Paleogeographically this area would be classified as a volcanic mountainous region because sufficient relief was created that erosion reached Precambrian crystalline rocks prior to deposition of Lower Triassic rocks. Deformation and metamorphism may extend as far east as the Cave Mountain area where Cameron and others (1979) interpreted the Cave Mountain Sequence, which is probably Lower Triassic, to rest unconformably on previously deformed and metamorphosed Paleozoic carbonate rocks. No Upper Permian volcanic or plutonic rocks have been recognized from the Cave Mountain area, and igneous activity may not have extended this far to the east. It is, therefore, reasonable to interpret the western Mojave Desert to be a topographically irregular uplifted region. Volcanoes were probably present in the westernmost Mojave, but not to the east (i.e., Cave Mountain area) (Plate 1).

The data suggest that there is a transition from undeformed and little disturbed sequences in the eastern Mojave Desert and Arizona into the arc environment to the west. Much of the central Mojave Desert was probably emergent in the early part of the Late Permian time. The entire area was emergent in latest Permian (Ochoan) time. Lower Triassic rocks in the Soda Mountains and the Clark Mountains contain clasts of volcanic and Precambrian crystalline basement rocks. Whether these rocks are locally derived or transported across the Mojave from deformed areas to the west is unknown. I tentatively favor local derivation because much of the Mojave Desert area has a cover of Lower Triassic marine rocks, making long-distance transport in Early Triassic time unrealistic. Whether relief responsible for bringing older rocks to the surface was produced mainly in

Permian time or also in Early Triassic time is uncertain. There is evidence for Late Permian deformation, but the presence of locally derived conglomerate in the Fairview Valley Formation, interpreted to be the result of Early Triassic faulting, leaves open the possibility of significant Early Triassic disturbances. Thus, the uplifted mountainous volcanic region in the western Mojave is interpreted to have given way to plains of lower relief to the east that were possibly disrupted by local large uplifts.

Rocks farther north in east-central California that received debris from the Antler Highland retained miogeoclinal trends throughout Mississippian time. Foredeep deposits of Upper Mississippian age in the Inyo Mountains are associated with the Antler Orogeny. Foredeep deposits in the Inyo Mountains are contiguous with similar rocks to the east. However, Mississippian and older trends are disrupted in Pennsylvanian time. From the Soda Mountains northwestward to the Inyo Mountains, patterns of sedimentation have different trends in Pennsylvanian and Permian time. Lower Permian rocks were deposited in several isolated turbidite basins that were apparently adjacent to highlands which did not receive deposition. Rocks in the basinal areas are as young as lower Guadalupian (?), and are overlain unconformably and paraconformably by upper Guadalupian shallow-marine rocks consisting of limestone and nonmarine chert-clast and limestone-clast conglomerate (Stone and Stevens, 1984a, p. 106). Up to 1800 m of Lower Permian turbidites are missing below this unit (Stone and Stevens, 1984a). Uppermost Permian rocks are missing, and the area was probably emergent at this time. It is unknown whether tectonism occurred in Upper Permian time (this point will be discussed below).

The tectonic and paleogeographic settings of Pennsylvanian and Permian rocks in east-central California have been interpreted by Stone and Stevens (1984a, p. 114) to be a continental-margin borderland similar to that of the present California coast. This conclusion was reached because the borderlands tectonic setting best accounts for rapid subsidence and uplift (with erosion) of isolated and segmented deep-water basins. I agree with this strike-slip-fault/borderland model for these basins. However, Stone and Stevens (1984a, p. 114-116) interpret the zone of strike-slip faulting to have existed along a continental margin that trended northwest-southeast from late Precambrian time onward. As discussed earlier, trends from late Precambrian through Mississippian time strike northeast-southwest across this area. Thus, I believe a more reasonable interpretation is that 1) strike-slip faulting started in Pennsylvanian or Early Permian time and was at a high angle to the original margin in this area; 2) miogeoclinal trends must end in the area of strike-slip faulting; 3) miogeoclinal sequences must be depositionally transitional over some distance into these basins, i.e., from eastern California and western Nevada into the area of the basins; and 4) as will be discussed below, this faulting reorganized the continental margin, changed its trend from northeast-southwest to northwest-southeast and led to a truncation of the miogeocline. With regard to this last point, I assume that the western part of the Mojave Desert, specifically the San Bernardino Mountains and the Victorville area, are relatively in place with respect to the eastern Mojave Desert. Later distortion of the Mojave Desert and thus the Permian strike-slip fault zone has occurred by oroclinal bending, and thrust, strike-slip, and normal faulting during Mesozoic and Cenozoic time. The modification of the continental margin by strike-slip faulting is based on the apparent

truncation of miogeoclinal trends and the creation of upper Paleozoic basins across the older trends; no strike-slip fault has yet been identified that is demonstrably part of this zone.

Whether strike-slip translation continued through Late Permian time is not well constrained. However, Upper Permian rocks were deposited in shallower water, and I interpret them to have been deposited after faulting ceased. For the purposes of this work, I consider strike-slip faulting to have ended sometime during the Guadalupian; in this view the Upper Permian rocks represent deposition along a newly established continental margin that trended northwest and faced west. Thus, the area from the Inyo Mountains to the Soda Mountains was probably emergent or received only thin, shallow-water deposits in Late Permian time (Plate 1).

Pennsylvanian and Lower Permian rocks in the El Paso and Lane Mountain areas are deep-water deposits that are interpreted by M.D. Carr and others, (1984, p. 92) to have been laid down in a rift environment. I prefer to interpret the tectonic setting of these sequences to be similar to that interpreted for the Inyo Mountains: a borderland/strike-slip-fault setting. This interpretation seems to explain better the complicated distribution of late Paleozoic rocks in the different structural blocks present in the El Paso Mountains and Lane Mountain areas, because rocks of various ages from Mississippian through Permian are deposited on the lower Paleozoic basement in each of these blocks.

Lower Permian turbidite sequences in the northwestern Mojave assemblages became volcanoclastic starting in upper Leonardian time. These rocks are overlain by andesites of probable Late Permian age. The entire Paleozoic sequence in the northwestern Mojave was subsequently deformed, metamorphosed, and intruded. One gneissic pluton in the El Paso Mountains

has been dated at 249 ± 3 Ma (U/Pb zircon, M.D. Carr and others, 1984, p. 91) and is intruded by other Upper Permian rocks. This indicates that deformation and plutonism occurred in Late Permian time. Considering the association of andesitic volcanism and granitic plutonism, deformation probably occurred in an arc setting. Hence, I interpret this area to have been in a strike-slip setting during Pennsylvanian and Early Permian time, and to have changed to an arc setting in Late Permian time.

Because the Late Permian tectonic setting of the northwestern Mojave rocks is similar to that of the western Mojave Desert, I consider the two areas to have been in close proximity in Late Permian time. If strike-slip faulting had ceased by Late Permian time, these areas may have been in their present relative positions by then. We can document their juxtaposition by Early Triassic time. If this is true, then a magmatic arc was present across the western Mojave Desert. Paleogeographically, the northwestern Mojave was probably an elevated volcanic region.

Rocks in the Shadow Mountains (Figure 4) may have experienced borderland deformation in late Paleozoic time. Lower Paleozoic rocks are cratonal or cratonal-transitional in character, and Carboniferous and/or Permian rocks are deep-water, mass-flow deposits. However, the age of the deep-water rocks is not well established, so their paleogeographic affinity -- whether Antler foredeep or borderland basin -- is unknown. Because Mississippian Antler flysch nowhere rests on lower Paleozoic rocks of cratonal or cratonal-transitional paleogeographic affinity in the western part of the miogeocline, the upper Paleozoic rocks are better considered to be Inyo Mountain borderlands facies rather than rocks of the Antler foredeep. Hence, the facies of these Late Paleozoic rocks may occupy a transitional position between those of the El Paso Mountains and

those of the western Mojave Desert (San Bernardino Mountains and Victorville areas). Irrespective of the affinities of upper Paleozoic rocks in the area, the Shadow Mountains must lie along or near the zone of Permian borderland activity, because out-of-place rocks are exposed immediately to the north and cratonal rocks immediately to the south. Also, because Permian and Pennsylvanian rocks in the western Mojave cratonal-transitional sequences have not been studied in detail, rocks of borderland affinity may be present there as well.

The last area to be considered in constructing the Late Permian paleogeography is western Nevada. Late Paleozoic rocks in the Mina area, consisting of Upper Mississippian limestone and Lower Permian chert grits of the Diablo Formation, rest on the lower Paleozoic eugeoclinal rocks of the Roberts Mountain Allochthon. The Mina area apparently lies east of the region affected by borderland deformation, and was emergent during Late Permian time. The Mina area is in the Antler Highland, and in Late Permian time the Antler belt continued as a positive topographic element into northern Nevada, and supplied clastic material into the Late Permian basin to the east (Peterson, 1980; Morgan, 1980).

So far little attention has been given to rocks of the Havallah basin. This area will be dealt with in following sections on the Sonoma Orogeny and its relation to Permo-Triassic tectonics.

Late Permian Tectonic Setting

Three major tectonic elements in the middle and Late Permian tectonic setting of the western United States are identified from the paleogeographic setting presented above. The first element is the remnant miogeoclinal basin that trends from southern California and Arizona

northward through Utah and Nevada. The miogeocline is bounded to the east by the Uncompahgre-San Luis, Defiance, and Kaibab uplifts of the Ancestral Rocky Mountains, built across the Transcontinental Arch, and to the west by the Antler Highland. These areas were tectonically stable at this time and were unaffected by events on the continental margin to the west. Also, the area received limited deposition during Guadalupian time, and was emergent during Ochoan time.

The second element is the magmatic arc developed on the southwestern corner of the continent, specifically in the western Mojave Desert. This arc is represented by igneous activity, deformation, and metamorphism in the El Paso Mountains, at Lane Mountain, and in the Victorville area. The arc was Andean in nature in the the western Mojave Desert, but the nature or presence of the arc to the north and south of this area is not established. A direct and rather abrupt transition to the craton to the east is inferred. However, the effects of Late Permian deformation and igneous activity may extend as far to the east as the Clark Mountains and the Soda Mountains, because clasts derived from Precambrian crystalline basement and upper Precambrian sedimentary rocks, as well as volcanic rock, are present in the Lower Triassic sections in these area. The area affected by deformation and uplift may have extended to the Spring Mountains, where Lower Triassic rocks appear to shoal and progressively on-lap older Permian rocks to the west. Collinson and Hasenmueller (1978) imply that the uplifted belt in the Spring Mountains was possibly connected with that of the Antler belt in central Nevada. Such a correlation implies a radical departure from Late Permian paleogeographic trends in southern Nevada, and if correct would imply that Early Triassic northwest-southeast trends were imprinted on the Cordillera far to the east and that

deformation or uplift occurred this far to the east. Such correlation must be considered speculative, because Lower Triassic rocks are not exposed to the between the Currie area and the Spring Mountains.

The third major element is the borderland strike-slip basins present between the Inyo Mountains and the Soda Mountains, and possibly extending as far west as the Shadow Mountains. Eugeoclinal rocks of the northwestern Mojave were part of this zone through Leonardian into Guadalupian time. Activity in this belt probably ceased in Late Permian time. Uplift related to tectonic activity outboard may also have begun in Guadalupian time; this uplift is recorded by thick chert-pebble conglomerate intermixed with shallow-marine rocks that are locally present in the Inyo Mountains, and chert grits of the Diablo Formation in western Nevada.

Early Triassic Paleogeography

The paleogeography of the southwestern United States in Early Triassic time is more complicated but better understood than in Late Permian time. Paleogeographic trends are similar to those of Permian time in the eastern part of the Cordillera, but there are important differences to the west. Triassic time will be subdivided into as many time slices as possible (see Figure 2). In the Mojave Desert area, however, ages of rocks and events are less well constrained than other areas, and only one time slice for Early Triassic time is presented.

A major regression at the end of the Permian led to the development of the pronounced Permo-Triassic paraconformity that is present in the western United States (and around the world). The shortest time represented by the paraconformity is in the area of the late Permian euxinic basins in northwestern Utah, northeastern Nevada, and southern Idaho. Here, rocks of

Griesbachian age rest on rocks of late Guadalupian age: only strata representing the latest Permian, Ochoan Stage are missing.

Deposition resumed along the miogeocline in Early Triassic time. The position of the depositional trough (here considered troughlike because it was probably bounded by highlands on both sides) was the same as in Late Permian time. Lower Triassic marine rocks can be traced from Idaho and Wyoming into southern California. The following data show that deposition was transgressive from north to south along the trough: 1) rocks of Griesbachian age with conodonts of the Early Triassic Hindeodus typicalis zone are present in the north (Figure 2; Carr and Paull, 1983, p. 46); 2) southward into central and southern Utah and Nevada the base of Lower Triassic rocks is younger, probably Smithian in age (Collinson and Hasenmueller, 1978); and 3) only Spathian faunas have been reported in Moenkopi-equivalent rocks in the Providence Mountains (Hazzard, 1954, p. 28). Deposition in the center of the trough occurred in quiet water, whereas deposition along the eastern, and in part western flanks, as well as along the advancing southern boundary, was shallow-marine to nonmarine in character.

Transgressive onlap of the western edge of the trough in central Nevada has been suggested by Collinson and others (1976) and Collinson and Hasenmueller (1978). These authors documented the deposition of lower Smithian rocks in the center of the basin, whereas onlap of Triassic rocks onto the western flank did not occur until upper Smithian time. Early Triassic erosion cut into the underlying Permian rocks; clasts in conglomerate deposited in erosional channels were probably locally derived.

Carr and Paull (1983) interpreted the facies patterns in Lower Triassic rocks of central and northern Utah and Nevada to indicate that the basin transgressed to the south and opened to the west into north-central Nevada. Westward opening of this basin is difficult to evaluate, because 1) the oldest Triassic sedimentary rocks present in central Nevada are Spathian, and rest unconformably on Lower Triassic rhyolite and intrusive rocks of the Koipato Formation (Silberling and Wallace, 1969), and 2) no Lower Triassic sedimentary rocks rest on the Antler highland in central Nevada. One of the principal reasons to assume that the Early Triassic basin opened to the west is the lack of facies on the west side that correspond to those on the east side. I interpret the lack of a symmetric facies distribution, such as the absence of redbeds and inner-shelf facies rocks of Carr and Paull (1983) onto the Antler Highland, to be the result of a change in the pattern and type of sediment source rocks and not of a westward opening of the Early Triassic basin. Carr and Paull (1983, p. 44-45) define their inner-shelf facies as "fine-grained sandstone, coarse-grained siltstone, and silty limestone." Clearly, if a source of abundant terrigenous material was lacking on the west side of the basin, i.e., if the Antler Highland was very subdued, then important components into the shelf facies and red-bed facies would be missing or greatly reduced. Hence, quartzite and arkosic redbeds are missing on the subdued Antler Highland; rocks richer in biogenic material are present. Stewart and others (1972b, p 77-81) have identified an uplifted area that provided abundant debris for the nonmarine facies of the Moenkopi Formation (Figure 24). Collinson and others (1976) found no strongly uplifted sources to the west, but did document onlap and some conglomerate that records exposure of the western margin of the Early Triassic basin. In fact, the lack of Lower

Triassic rocks on the Antler Highlands supports the interpretation that the Antler belt remained a positive topographic element at this time, and that the Early Triassic basin was bounded by highlands on both sides.

The remnant miogeoclinal basin probably extended as far south as the Providence Mountains. The Virgin Limestone Member and other marine rocks of the Moenkopi Formation are present here, and record sedimentation in the central, marine portion of the remnant miogeocline. These rocks probably graded into rocks of shallow marine and nonmarine clastic facies farther to the southeast in California. Hence, the belt of marine to nonmarine rocks is continuous into this area, and it can be followed southward from Wyoming into California and Arizona along the western flank of the Transcontinental Arch and Ancestral Rocky Mountains.

There is a transition from rocks of the remnant miogeocline westward into orogenic sequences in the Mojave Desert. Lower Triassic rocks in the Clark Mountains and the Soda Mountains contain minor conglomerate with clasts of limestone and chert, and more importantly clasts of metasedimentary, gneissic, plutonic, and volcanic rock, and are interbedded with nonmarine sandstone in the Clark Mountains and marine limestone and calcareous siltstone in the Soda Mountains. The gneissic and metasedimentary rocks were probably derived from the upper Precambrian clastic sedimentary rocks and Precambrian crystalline basement rocks in the area. Structures that brought the older rocks to the surface can no longer be identified; regional considerations suggest however, that the structure must have developed in Late Permian or earliest Triassic time. At least in the Clark Mountains, the clasts were derived from the west (Walker and others, 1983).

Conglomerate becomes more abundant in the Lower Triassic rocks to the west in the Cave Mountain and Victorville areas (Figure 4). Rocks in the Cave Mountain area contain abundant volcanic clasts and arkosic sandstone. Hence, strata in this area record the mixing of quartzose sediments derived from the east and south, such as those present in the New York Mountains and around southeastern California, with material of probable arc derivation to the west. In fact, because the Paleozoic rocks in the Cave Mountain area are inferred to have been deformed in Permo-Triassic time, prior to deposition of the Cave Mountain Sequence, arc material may be partly locally derived. In the Victorville area the Fairview Valley Formation contains abundant, locally derived clasts of plutonic, volcanic, gneissic, and metasedimentary rocks. Syndepositional faulting is recorded by a conglomerate wedge near the top of the section. A shallow-marine depositional setting is required for these rocks because of the presence of burrowed siltstone, carbonate beds containing conodonts, and mudcracks. The paleogeographic setting of Lower Triassic rocks at Cave Mountain and Victorville is interpreted as shallow-marine to nonmarine plains surrounding local emergent highlands (Plate 2). This setting was probably inherited from a mountainous or hilly region that was created and partially eroded in Late Permian time (Plate 1).

A similar setting is appropriate for rocks of the northwestern Mojave assemblage in the El Paso Mountains and at Lane Mountain. The Lower Triassic rocks contain calc-silicate hornfels interlayered with conglomerate with locally derived clasts that presumably overlie out-of-place Antler belt rocks and Upper Permian arc rocks. The overlap of probable Lower Triassic sedimentary rocks that are paleogeographically similar to those in the western Mojave Desert constrains this juxtaposition

of out-of-place rocks with the craton to have been completed by sometime before Early Triassic time, although the presence of Upper Permian arc rocks probably connects the northwestern Mojave rocks to the craton by Late Permian time.

In summary, the Lower Triassic overlap sequence permits reconstruction of paleogeography of the Mojave Desert area during Early Triassic time. Early Triassic deposition in the northwestern and western Mojave Desert occurred in intermontane marine basins, where a complicated pattern of highlands shed debris into intervening, shallow-marine basins. Hence, northwestern Mojave eugeoclinal rocks and western Mojave cratonal rocks share a common Early Triassic paleogeographic setting (Plate 2).

Rocks of the Candelaria Formation rest on rocks belonging to the Roberts Mountains Allochthon in the Mina area, southern Toiyabe Range, and probably in the Saddlebag Lake Pendant. The Candelaria Formation contains a lower sequence of Griesbachian and Dienerian age consisting of marl, mudstone, and limestone, and an upper sequence of feldspathic and volcanoclastic siltstone and sandstone. I correlate the lower part of the sequence with rocks of similar age and lithology to the south in the Inyo Mountains. Sedimentary structures suggest that the rocks in both areas were deposited in initially shallow then deep water. Rocks in the Argus Range were deposited in shallow water during Griesbachian and Dienerian time, but grade into progressively deeper-water rocks northward in the Inyo Mountains and areas underlain by the Candelaria Formation.

Thus, Lower Triassic marine rocks are continuous from the Mojave Desert northward into east-central California, specifically in the Inyo Mountain area and farther north into the Mina and Saddlebag Lake areas. However, older Lower Triassic rocks are present in the sections toward the

north. Rocks at Union Wash and Mina contain Griesbachian and Dienerian strata, i.e., lower Lower Triassic, whereas those in the Soda Mountains to the south contain only Spathian rocks, i.e., upper Lower Triassic. The Lower Triassic rocks are thus transgressive from north to south, representing progressive southerly onlap of strata. Sedimentary rock types are very similar in all of these areas, although thickness and lithology vary considerably because of the presence of locally derived conglomerate. All these areas, with the exception of the Mina area, were uplifted and received deposits of nonmarine sedimentary and volcanic rock commencing in early Middle or latest Early Triassic time. These data imply that a continuous marine basin existed during Spathian time from Idaho to southern California and then northward to central California (Plate 2).

The effects of the Early Permian continental-borderland tectonics and deposition are not evident in Early Triassic time. While some deep-water sedimentation occurred locally in the Inyo Mountains and Darwin Hills, the Lower Triassic rocks are more uniform than Lower Permian rocks, and do not show evidence of much tectonic activity nearby.

The Permo-Triassic tectonic setting of rocks in the northwestern Mojave Desert are unlike that of similar rocks to the north in the Antler belt. In the Mina area, igneous activity and deformation of rocks of the Roberts Mountain Allochthon are absent in Late Permian and Early Triassic time, whereas magmatic arc activity and deformation affected the Mojave. However, volcanoclastic debris was shed into the Candelaria basin, recording the presence of an igneous source in the area. While Lower Triassic rocks constitute an overlap sequence for late Paleozoic deformation in the Mojave Desert, they are predeformational in the western Nevada area and at Saddlebag Lake. Thus, in the south, deformation

occurred in an intra-arc setting prior to deposition of the Lower Triassic overlap sequence, whereas in the north, deformation occurred in a foreland setting and postdated deposition of Lower Triassic strata.

The northward deepening of facies in western Nevada and east-central California is very important in constraining changes in paleogeography. The Antler Highland in western Nevada and extending to the Saddlebag Lake Pendant received little deposition until Permian time, even though it was probably never highly elevated (Burchfiel and others, 1985). In central Nevada, the Antler belt received some deposition in late Paleozoic time but was not the site of deposition in Early Triassic time. Hence, the presence of the Candelaria Formation contrasts strongly with sedimentation on the Antler highland elsewhere, especially because of its deep-water aspect, and indicates that the Antler belt behaved differently in its eastern to western parts.

Speed (1984) interpreted deposition of the Candelaria Formation to record the collision of the Sonomia island arc against North America, and the deep-water sedimentation to result from foreland depression in front of the advancing arc. I agree with this interpretation although I consider the final emplacement of Sonomia onto North America to have occurred probably in Jurassic time. Late Permian paleogeographic trends in the Antler belt at Mina and in central Nevada apparently followed those established in Early Mississippian time. Early Triassic paleogeographic trends, however, change as they are traced from central Nevada into the Mina and Saddlebag Lake areas; the former Antler belt was submerged and received deposition of deep-water rocks in eastern California, whereas the Antler belt in central and northern Nevada was apparently still emergent.

The presence of Lower Triassic marine rocks in the Mina area that apparently connect with rocks in the Inyo Mountains and south to the Mojave Desert reinforces the northwest-southeast trend of paleogeographic belts at this time. If a highland existed from the Antler belt to the Spring Mountains, then northwest trends present in the Mojave may continue far to the north, indicating that such trends were well established throughout the Cordillera in Early Triassic time (Plate 2).

The Early Triassic paleogeographic trends, generally oriented north-south or northeast-southwest, are similar to those of Permian time in the eastern and northern parts of the western United States. Trends in southern California and southern Nevada, however, follow new northwest-southeast directions. Three important conclusions are reached from these features and from data discussed above. First, the change from older paleogeographic trends was completed by Early Triassic time. Second, a convergent margin was established on the southwestern edge of North America in Late Permian time. Third, out-of-place Roberts Mountain Allochthon rocks in the northwestern Mojave Desert were in place and juxtaposed against North American cratonal and transitional rocks by Early Triassic time.

Early Triassic Tectonic Setting

The southwestern United States was more stable tectonically in Early Triassic time than in Permian time. In western Nevada, however, deformation and reorganization of the continental margin began at this time, whereas it had already occurred in the Mojave area. Deformation was still active in the Mojave, but at a much reduced level. In the Victorville area there is evidence for faulting during deposition of the Fairview Valley Formation, and volcanic rocks present in the Bond Buyer

Sequence in the El Paso Mountains indicate that the magmatic arc was still active. Hence, deformation and igneous activity in Early Triassic time attest to continuing activity in the arc region. Arc activity was relatively minor at this time, but became much more pronounced by Middle Triassic time.

Western orogenic sequences grade eastward into rocks that were deposited on a relatively stable craton. Tectonism in the east cannot be clearly identified, and the paleogeography in the easternmost Mojave Desert appears to follow Paleozoic trends. Deformation which brought Precambrian crystalline rocks to the surface as a source for clasts in Lower Triassic rocks can only be dated as Permo-Triassic and may be of earliest Triassic age.

An important question concerns the relationship of the Sonoma Orogeny in Nevada to events in the Mojave Desert. The connection between events in these two areas is probably best interpreted from geologic relations in the Mina area and the Inyo Mountains. The Sonoma Orogeny in Nevada is recorded by two major structural and stratigraphic features: 1) the deformation of the late Paleozoic Havallah oceanic sequence and unconformable overlap of the Havallah by the Lower Triassic Koipato Rhyolite; and 2) subsidence and deposition of the Candelaria Formation with deposition of volcaniclastic debris in its upper part. Many authors (e.g., Silberling and Roberts, 1962) consider emplacement of the Golconda Allochthon, the structural element containing the Havallah sequence, to have occurred during the Sonoma Orogeny.

Complicating the interpretation of the Sonoma Orogeny, however, is the lack of an unequivocal sedimentary overlap sequence on the Golconda thrust or the shedding of debris of the Golconda Allochthon into a foredeep basin.

Thus, in central Nevada the tie of Golconda Allochthon to North America is tenuous. In the Mina area, Speed (1977, 1978) interprets rocks in the upper part of the Candelaria Formation to record the emplacement of the Black Dyke Formation rocks (here representing Sonomia) onto the North American continental edge. Structurally intervening Pennsylvanian to Lower Triassic rocks were assigned by Speed to the Golconda Allochthon and considered by him to have been emplaced at this time. However, no debris from the Golconda Allochthon is present in the Candelaria Formation. Also, the age of juxtaposition of Black Dyke, Golconda, and Candelaria rocks is permissibly as young as Jurassic, much younger than the Candelaria Formation. Lastly, Golconda rocks are partly coeval with the Candelaria, but do not contain debris from the Black Dyke Formation although they are inferred to have been deposited originally in an area between the Candelaria and Black Dyke structural units. These points detract from the interpretation presented by Speed and others (1977; Speed, 1978, 1984) for the timing of emplacement of the Golconda Allochthon. Hence, emplacement of the Golconda Allochthon and the nature of the Sonoma Orogeny are still not fully resolved.

An alternative interpretation for the rocks of the Golconda Allochthon in the Mina area is that they are displaced fragments of the borderland belt. The rocks lack the greenstone that is characteristic of many of the Havallah sections, but are lithologically similar to turbidites in borderland assemblages. These rocks can be interpreted to have been caught structurally in the collision zone of the Sonomian arc when it finally collided in post-Early Triassic time, and subsequently interleaved with Sonomia and North America during Jurassic thrusting.

The relation of deformation during the Sonoma Orogeny with events in the Mojave Desert is one of strong contrasts. The nature and timing of the events are different: 1) deformation in the Mojave Desert is accompanied by metamorphism and igneous activity, whereas deformation in the Mina area is essentially nonmetamorphic; 2) deformation in the western Mojave was probably the result of east-directed subduction beneath the margin, but in the Mina area deformation was apparently related to westward underthrusting (subduction?); and 3) deformation in the Mojave is Late Permian whereas that in the Mina area is late Early Triassic. Overriding of the North American Plate in the Mina area by Sonomia and the Golconda Allochthon is recorded by deepening of the Candelaria basin, an effect that may have been present as far south as the Inyo Mountains.

Subsidence of the Inyo Mountains was followed by uplift and deposition of conglomerate in late Spathian (?) or early Middle (?) Triassic time. The subsidence may be the result of overthrusting by Sonomia, and the uplift caused by eastward migration of igneous activity in Late Early and Middle Triassic time.

Uplift of the Antler Belt and deposition of conglomerate in eastern Nevada has been related to the Sonoma Orogeny by Collinson and Hasenmuller (1978). However, the kinematics envisioned for the Sonoma Orogeny, i.e., thrusting of a wedge of deformed oceanic rocks of the Havallah Sequence onto the continental margin, should cause subsidence rather than uplift in the foreland. Hence, I interpret deformation of the craton and the extent of overthrusting of the Golconda Allochthon during the Sonoma Orogeny to have been minor, with the probable exception of the Mina area, and the remnant Antler Highland to have been only mildly disturbed during this event.

In summary, the Late Permian continental margin has three main tectonic and paleogeographic elements (Plate 1): 1) a remnant miogeoclinal basin in Nevada, Utah, Idaho, and, in Early Permian time, southern California, bounded by the Ancestral Rocky Mountains and Transcontinental Arch to the east and the Antler highland to the west; 2) cratonic emergent areas to the south that were transitional across the Mojave Desert into a magmatic arc built across the southwestern edge of the craton and the out-of-place Roberts Mountain Allochthon rocks in the the northwestern Mojave Desert; and 3) an uplifted and emergent borderland in east-central California.

The Early Triassic paleogeography and tectonic setting is similar to that in Late Permian time in Utah, Arizona, and eastern Nevada (Plate 2). To the west, in California and western Nevada, paleogeographic trends are demonstrably reoriented to northwest-southeast in Early Triassic time. Arc activity along the southwestern margin is subdued compared to Late Permian time. A connected seaway from Idaho to Southern California to Mina was apparently established by Spathian time, and it closed around the southern end of the Antler Highland and a highland present north of the Spring Mountains.

Extension of the Miogeocline into Mexico

Scattered exposures of Paleozoic rocks are present in northern Mexico and are probably equivalent to rocks of the miogeocline. The best studied sections are around Caborca, Sonora. Upper Precambrian and Cambrian rocks exposed near Caborca are lithologically similar to rocks in the Death Valley area, California (Figure 29; Stewart and others, 1984). In the El Capitan area, rocks of Paleozoic and Early Triassic age are present, and

have cratonic affinity (Leveille and Frost, 1984). Rocks correlated with the Kaibab Formation and older formations are overlain by rocks correlated with the Moenkopi Formation. This relation suggests that the miogeoclinal and cratonal rocks extended south to northern Sonora. It is unlikely that rocks in Sonora were significantly displaced in post-Paleozoic time, because facies of Lower Triassic rocks in the western Mojave Desert are unlike those exposed at El Capitan. However, the structural geology of northern Mexico is poorly understood, so correlations may have to be altered if significant structural complications become evident.

Limits of Post-Early Triassic Terrane Accretion

The Lower Triassic overlap sequence, along with the distribution of Precambrian and Paleozoic rocks belonging to North America, constrain the area in which significant Mesozoic and Cenozoic structural displacement of rocks has occurred and the outer limit for accretion of exotic terranes. All areas which contain the Lower Triassic overlap sequence are exempt from major translations in later time, such as that proposed by Silver and Anderson (1974) and Anderson and Silver (1979).

Middle Triassic Arc

Although Upper Permian arc rocks are relatively scarce, Middle Triassic ones are widespread. Probable or dated Middle Triassic volcanic rocks are present in the Victorville area, Soda Mountains, Devils Playground, Cave Mountain, Inyo Mountains, and Saddlebag Lake Pendant. (Descriptions of these rocks are given in previous chapters.) Middle Triassic plutonic rocks are known from the Granite Mountains (C.F. Miller, 1978), Mount Lowe in the San Gabriel Mountains (Silver, 1971), the

Yerrington area of western Nevada (Dilles and others, 1983), the San Bernardino Mountains(?) (Cameron, 1981), the El Paso Mountains (Cox and Morton, 1982), and in scattered exposures in southern Arizona (B.C. Burchfiel, oral communication, 1985). Hence, arc-related magmatism of Middle Triassic age stretches along the length of the southern United States Cordillera, and extended farther eastward than Late Permian arc rocks (Figure 25). This adds another constraint on the change from northeast-southwest trends to northwest-southeast trends.

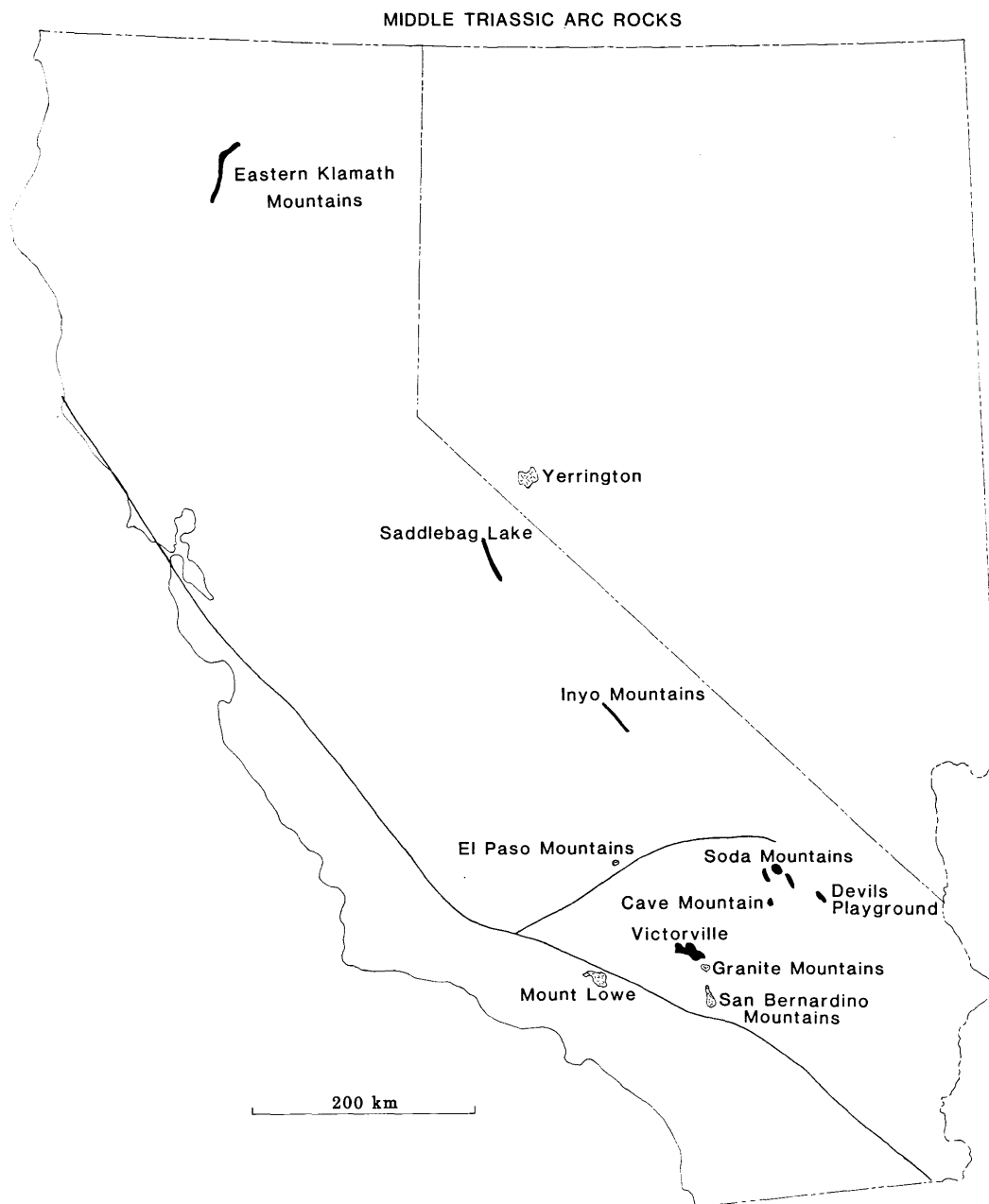
Suggestions for Nomenclature

I propose two new names for use in describing Permo-Triassic development of the southwestern United States. I suggest the name Sidewinder event to encompass Late Permian deformation and igneous activity in the El Paso Mountains, Lane Mountain, and Victorville areas. This event is best dated at Black Mountain in the Victorville area and in the El Paso Mountains. At Victorville, deformation preceded intrusion of monzonite at 242 Ma. In the El Paso Mountains, voluminous Upper Permian andesite was deformed and intruded by Upper Permian plutons.

I suggest that Lower Triassic rocks in these areas be referred to as the Sidewinder overlap sequence. Rocks included in this sequence are the Fairview Valley Formation, Bond Buyer Sequence, Noble Well Formation and the Cave Mountain sequence. Unequivocal overlap of deformation can only be demonstrated in the Victorville area, where Lower Triassic Fairview Valley Formation rests unconformably on deformed Paleozoic strata and Upper Permian monzonite.

The name Sidewinder is used because relations for the deformational event and its overlap are clearest near Sidewinder Mountain and Sidewinder Valley in the Victorville area.

Figure 25: Middle Triassic rocks considered to be related to magmatic arc activity. Black: volcanic rocks; pattern: intrusive rocks. Data from this study, Dilles and others (1983), C.F. Miller (1978), and Cox and Morton (1980).



CHAPTER 6: Margin Modification

One possible interpretation of the late Paleozoic tectonic development of the southwestern United States is that the continental margin was truncated by strike-slip faulting, and that a magmatic arc was built along the newly formed margin. (For other interpretations see Chapter 1.) This is the interpretation that I favor in this thesis. In this chapter I focus on this truncation event and present interpretations for the timing and processes involved in truncation, since one of the important aims of this study is to interpret data concerning when and how the southwestern margin of the North American continent was modified. Tectonically, this event involved the truncation of the miogeocline and craton, displacement of the northwestern Mojave rocks, and construction of an Andean arc along the newly formed northwest-southeast trending North American margin. The most appealing mechanism proposed for the continental-margin truncation is strike-slip faulting to form a new and reoriented margin in Permian time (first suggested by Burchfiel and Davis, 1972). This mechanism can easily account both for material having been removed from the continent and for the juxtaposition of eugeoclinal rocks in the northwestern Mojave Desert with coeval rocks of unlike facies in the Mojave Desert.

Stratigraphic features suggestive of transcurrent faulting are abundant. One of the most compelling pieces of evidence is the turbidite basins that are present in east-central California between the Inyo Mountains and to the Soda Mountains. Stone and Stevens (1984a) have interpreted these basins to have formed by strike-slip faulting in a continental borderland, and they have documented a complicated pattern of basin subsidence and uplift, with possible associated compressional

deformation (Stevens and Stone, 1985). This led them to suggest that the truncation of the margin was a Pennsylvanian and Permian feature, but that the margin already had a northwest-southeast trend in Pennsylvanian time (Stone and Stevens, 1984b), and that it had this trend from late Precambrian time onward (Stone and Stevens, 1984a, p. 115-116; Dickinson, 1977). In this interpretation, rocks of the El Paso Mountains and at Lane Mountain are basically in place in their present positions, and were part of the borderland during late Paleozoic time (Stone and Stevens, 1984a, p. 115).

Contrary to the interpretation of Stone and Stevens, the eugeoclinal rocks in the northwestern Mojave Desert probably were derived from a position several hundred kilometers to the north, because: 1) rocks of Roberts Mountain Allochthon can be traced without break or change in trend into the Saddlebag Lake Pendant of the Sierra Nevada; and 2) facies trends and the paleogeographic affinities of western Mojave Desert rocks are incompatible with having the northwestern Mojave rocks in proximity to the western Mojave until Late Permian time. The total lack of clastic rocks derived from the Antler belt in Mississippian rocks in the western Mojave Desert, and the parallelism of the Antler belt with Paleozoic paleogeographic trends in eastern California until the end of Mississippian time, strongly suggest that rocks in the northwestern Mojave Desert are out of place and were once continuous with the Antler belt exposed farther to the north.

The age of last movement on the truncation boundary is fairly well constrained. Since out-of-place rocks are overlain by the Lower Triassic overlap sequence, truncation and juxtaposition occurred prior to Early Triassic time. This is an upper limit, since these blocks may well have

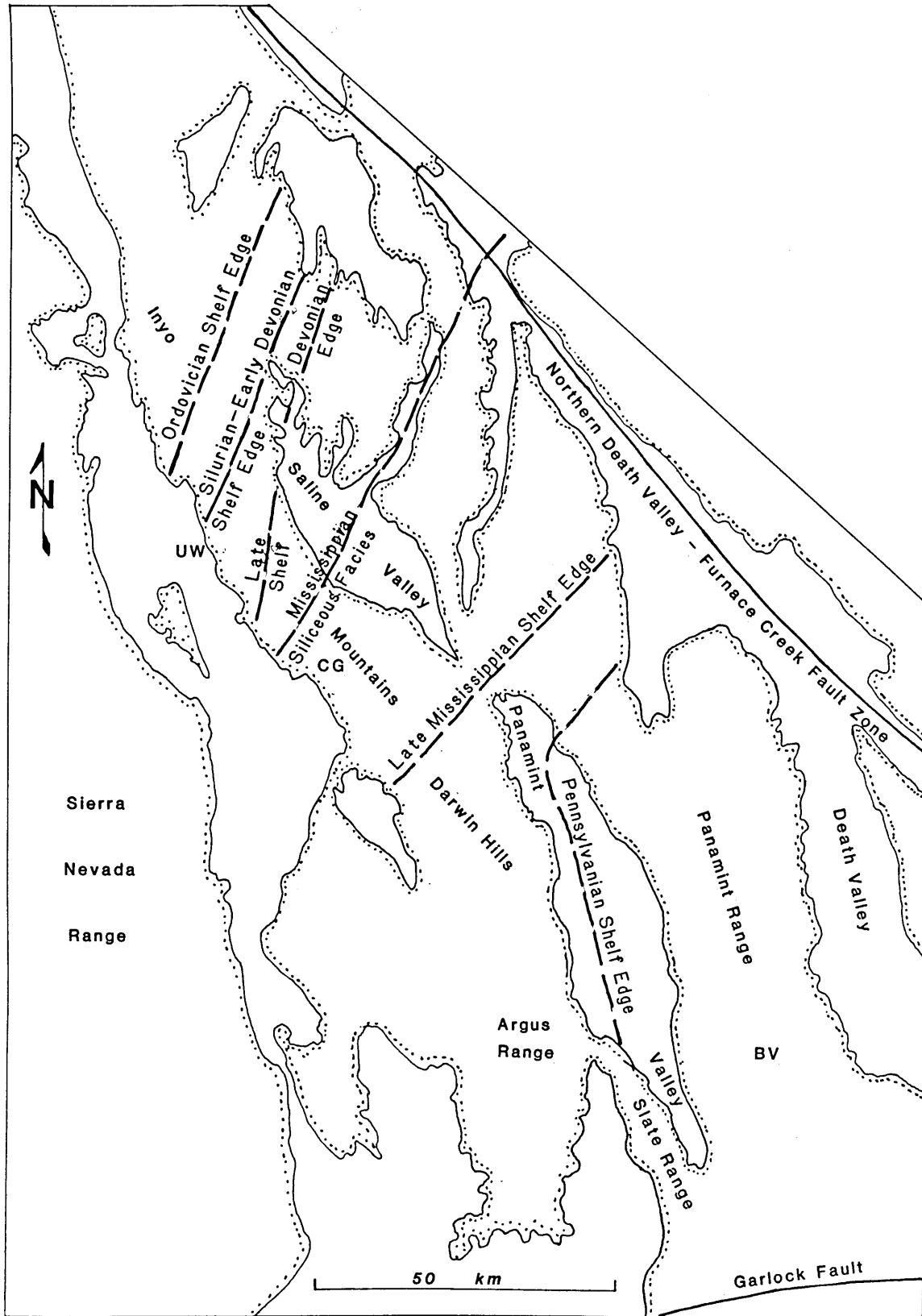
been together by sometime in the Late Permian, because Upper Permian igneous rocks and deformation are present in both of these areas. Also, paleogeographic trends in Early Triassic time were northwest-southeast, demonstrating that the continental edge had been reoriented by this time.

Initiation of the truncation event is less well timed. The Roberts Mountains Allochthon and the Mississippian Antler flysch trough form a continuous belt across Nevada and east-central California, so strike-slip faulting apparently postdated Mississippian time. Stevens (1984) documented the southeastward migration of the slope-shelf break throughout Cambrian to Mississippian time in eastern California (Figure 26). The boundary trended mainly north-northeast over this time period, but changed to northwest in Pennsylvanian time. Depositional trends of Pennsylvanian slope-facies rocks in eastern California cut across older Paleozoic trends, and suggests that truncation of the continental margin may have started in Pennsylvanian time (Stone and Stevens, 1984a, p. 115-116; Figure 26).

The most intense period of deformation apparently was in Early Permian time. Numerous small basins were created in east-central California and extended between the Inyo Mountains and the Soda Mountains; turbidites were deposited in these basins, and resedimented shallow-water fauna, debris flows, and olistostromes are common (Stone and Stevens, 1984a). Stevens and Stone (1985) have reported thrusting of probable middle Wolfcampian age in the Inyo Mountains. Rocks of Lower Permian age in the El Paso Mountains are lithologically similar to those in the Inyo Mountains.

Stevens (1982) documented a facies distribution in Early Permian time different from that in older Paleozoic time by mapping the distribution of the Thysanophyllum coral belt in the western United States. This belt follows northeast-southwest trends into the Death Valley area, and shifts

Figure 26: Detailed Ordovician to Pennsylvanian paleogeographic trends in east-central California. From Stevens (1984), Stone and Stevens (1984), and Dunne and others (1981). Dots and thin solid lines show the outlines of mountains ranges in the area.



Facies Trends in East-central California

to a more northwest-southeast orientation in the northeastern Mojave Desert.

The data reviewed above suggest that truncation began after Mississippian time, possibly as early as Pennsylvanian time, and was surely in full stride by Early Permian time.

I agree with many of the interpretations of Stone and Stevens (1984a, 1984b). In particular, it seems reasonable that Pennsylvanian rocks record a northwest trend for part of the margin, and that a southeast bend in the edge of the miogeocline was fully developed by Permian or Pennsylvanian time (Figure 26). However, I interpret Mississippian and older facies trends to be incompatible with the existence of a northwest-southeast trending margin prior to Pennsylvanian time, and that the northeast-southwest trend for the continental margin continued through Mississippian time. This is indicated by the continuity of the Late Mississippian Antler flysch belt across the area and the continuity of Early Mississippian facies patterns (Stevens, 1984). I also favor the idea that the Pennsylvanian and Permian rocks between the Inyo Mountains and Soda Mountains record truncation and reorientation of the margin during this time.

I agree that the Lower Permian and Pennsylvanian turbidite basins were probably formed in a continental borderland environment, in the sense that they are related to strike-slip faulting along a continental margin. The data presented above, however, suggest that the continental margin (along which the borderland developed) was formed during this late Paleozoic truncation event while the older margin was being truncated. In the borderland, upper Paleozoic deep-water rocks rest on shallow-water shelf rocks. Faulting and basin development appears to have progressed toward

the craton. The basinal rocks are oldest in the Inyo and Argus Ranges, and become progressively younger to the south into the Soda Mountains.

In any model for margin development, the northwestern Mojave Desert and western Mojave Desert rocks must be together by Late Permian or earliest Triassic time. Stone and Stevens (1984a) suggested that rocks in the San Bernardino Mountains and at Victorville were displaced from farther south in Mesozoic (?) time and that rocks in the northwestern Mojave were in place in middle and late Paleozoic time. As pointed out above, there is no evidence for deformation in the western Mojave miogeoclinal rocks prior to Late Permian arc activity, whereas there is evidence for displacement of the northwestern Mojave eugeoclinal rocks.

In fact, the southward translation of the northwestern Mojave Desert rocks may be tracked using the upper Paleozoic stratigraphy in sections from near Mina and east-central California. The oldest event present in the rocks of the northwestern Mojave Desert is deformation resulting in juxtaposition of eugeoclinal and transitional facies rocks in Devonian-Mississippian time. This event is common to all lower Paleozoic eugeoclinal rocks in the Roberts Mountain Allochthon, and thus it is reasonable to interpret the northwestern Mojave rocks as the western continuation of the Mina and Saddlebag Lake segment of the Antler belt. Deformed rocks in the El Paso Mountains are overlapped by Lower Mississippian argillite and conglomerate of local derivation (M.D. Carr and others, 1984, p. 88-89). This overlap of the Roberts Mountain Allochthon by Lower Mississippian rocks and the presence of Mississippian carbonates on the Roberts Mountains Allochthon at Mina led Burchfiel and others (1985) to suggest that the Antler Highland was topographically subdued to the west. Lower Mississippian argillite and conglomerate in the El Paso

Mountains are overlain by undated quartzose turbidites, in turn overlain by Pennsylvanian argillite, calcareous argillite, and quartzose turbidites. M.D. Carr and others (1984) inferred a Mississippian age for the undated rocks; however, the possibility that these rocks are Pennsylvanian cannot be dismissed. Shallow-water Pennsylvanian rocks grade upward into argillaceous and calcareous turbidites of Pennsylvanian and Permian age, which resemble the Pennsylvanian Keeler Canyon Formation of the Inyo Mountains. Hence, I infer that the truncation event had started and the northwestern Mojave rocks were near the northern Inyo Mountains by this time. Carr and others (1984) interpreted upper Paleozoic rocks in the El Paso Mountains to record rifting. Alternatively, I agree with Stone and Stevens (1984a) that these rocks probably record strike-slip-faulting/borderland tectonics.

Lower Permian rocks in the northwestern Mojave are also deep-water turbidite deposits, and they contain abundant resedimented shallow-water fossils, debris flows, and olistostromes. This is similar to the lithologic succession and source composition of the Lower Permian rocks throughout the borderlands area in the Argus Range, Darwin area, and Soda Mountains. Thus, the rocks of the northwestern Mojave Desert may have lain west of this area during Early Permian time; borderland deformation effects extended to the Soda Mountains, and may have affected faunal patterns as far south as the Devils Playground area (Stevens, 1982). Lastly, Upper Permian rocks and the Late Permian tectonic setting of the northwestern Mojave are identical to those in the western Mojave Desert, suggesting that these rocks were near their present position by Late Permian time. In addition, Lower Permian and older rocks in the San Bernardino Mountains and Victorville area give no indication that rocks of the Western Mojave Desert

are displaced from their present position (at least from our present understanding of these area; see e.g., Stewart and Poole, 1975; Cameron, 1981; and Brown, 1984).

I consider that late Paleozoic rocks in the western United States record the southward movement of the northwestern Mojave Desert rocks, and that this movement is most reasonably interpreted as having occurred by strike-slip faulting. Movement also truncated the old northeast-trending continental margin and established a new northwest-trending margin.

Davis and others (1978) and Burchfiel and Davis (1981) consider the displaced rocks of the Roberts Mountain Allochthon to constitute a sliver caught between the craton and a main truncation boundary to the west. I have presented evidence for the timing of sliver displacement but have not discussed the main truncation that removed the Antler belt and other material outboard of the present extent of North American rocks (including the sliver). Davis and others (1978, p. 7) considered this boundary to be marked by the $^{87}\text{Sr}/^{86}\text{Sr}$ 0.706 line (Figure 1) and that various oceanic rocks presently lie outboard of the boundary. Unfortunately, we cannot be sure that the boundary coincides with the one created in late Paleozoic time, because Mesozoic deformation and magmatism has been severe in the Sierra Nevada along the trace of the 0.706 line.

The present boundary between rocks belonging to Precambrian continental North America and the sliver of Roberts Mountain Allochthon has been placed at various locations and assigned various ages by other workers. Saleeby (1981, p. 166) considered this boundary to lie along his "Foothills Suture" and to have been active in Late Triassic to Middle Jurassic time. Deformation resulted in juxtaposition of exotic ocean-floor assemblages against North America. Schweickert (1981) and Schweickert and

Snyder (1981) considered the main truncation event to be Middle Triassic in age. However, these authors considered the El Paso Mountains rocks to be in place, and did not fully recognize the importance of Late Permian arc activity in the western part of the Mojave Desert.

All of the authors cited above considered the truncation event to postdate the Sonoma Orogeny because the Sonoma belt trends obliquely into the Sierra Nevada. This poses a timing problem for displacing the El Paso Mountain rocks and truncating the continental margin in late Paleozoic time and subsequently truncating the Sonoma belt at a later time. The simplest solution is to assign the truncation of the continental margin and displacement of the northwestern Mojave rocks southward from the Antler belt to the late Paleozoic and to truncate the Sonoma belt in Mesozoic time. The late Paleozoic truncation must have occurred, because of the presence of a Late Permian magmatic arc that developed within and across the boundary of different paleogeographic elements in the western Mojave. The Sonoma belt and probably the continental margin and arc were truncated in Middle Triassic and/or later time as recorded by 1) the missing extension of the Sonoma belt; 2) the abundant evidence for transform faulting in the Kings sequence and along the Foothills Suture (Saleeby, 1981); and 3) suspected Middle and Late Mesozoic truncation events in the Salinian block and Peninsular Ranges. Saleeby (1981), for example, has assigned some of these truncation events to the Mesozoic.

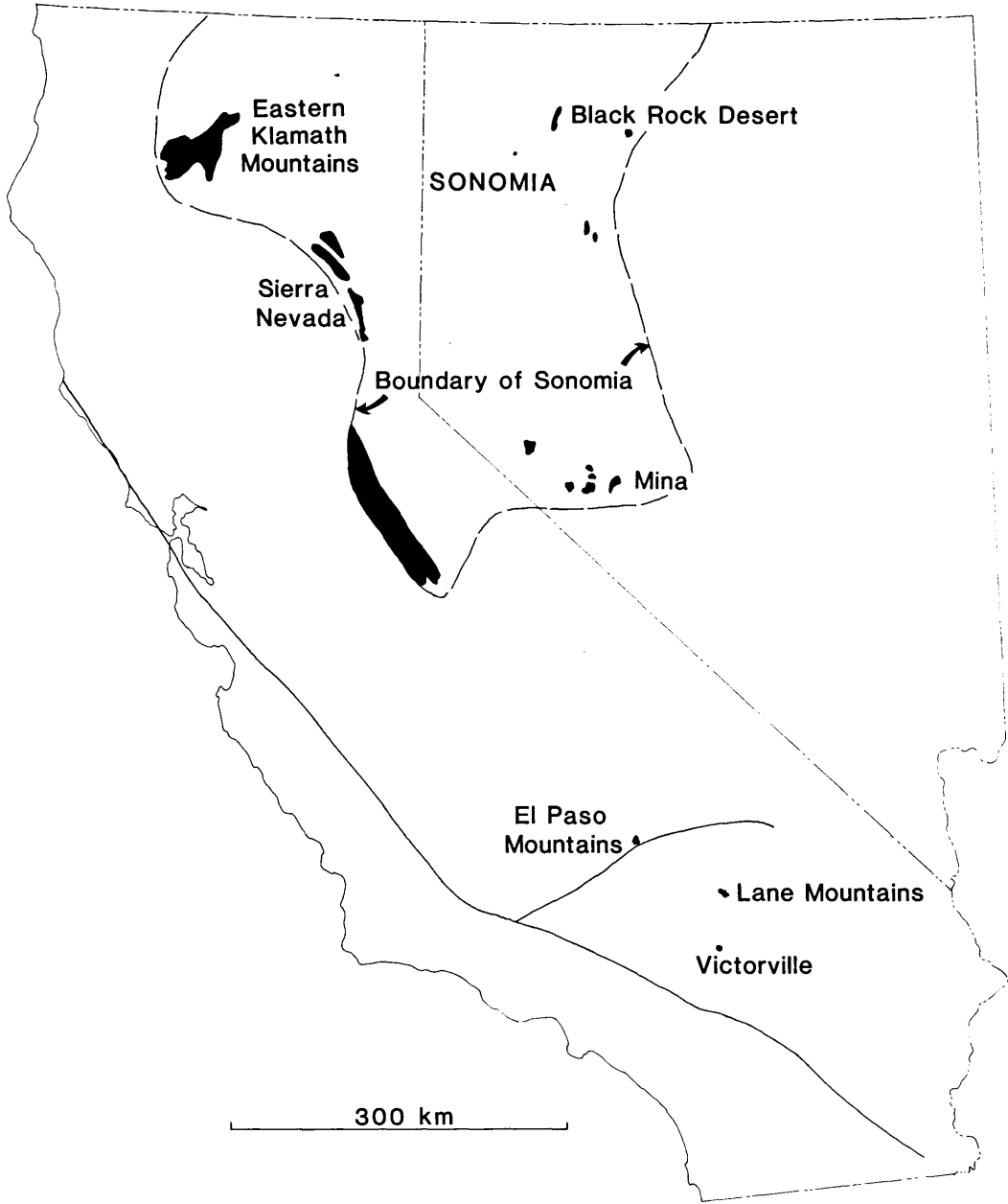
The continuity of Permian arc volcanic rocks exposed in northwestern and western Nevada Desert (the rocks which constitute the Sonomian microplate of Speed, 1979), with those in the western Mojave Desert and the Klamath and Sierra Nevada Ranges is unclear at present. The suturing of Sonomia with North America has been interpreted by Speed as late Early

Triassic because of the volcanic debris present in the Candelaria Formation. However, the evidence for thrusting in this area only constrains it to be pre-Early Cretaceous. Hence, if the interpretation based on the Candelaria Formation is rejected, then the timing of emplacement of Black Dyke and Mina Formations, i.e., suturing of Sonomia with North America, is not well established.

Permian andesitic volcanic rocks and plutons in the El Paso Mountains and Victorville area are coeval with those in Sonomia. These rocks may tie Sonomia with North America in late Permian time, although they do not constrain the time of suturing of Sonomia in Nevada. This model would imply that the arc in Late Permian time had a geography similar to modern Alaska, where the arc is connected with the craton in the Mojave and is Andean in character, but its northward extension as the Sonomia arc would be an island arc, analogous to the Aleutian chain. However, one major problem in defining the limits of Sonomia is the lack of material identified with this microplate. Although exposures of upper Paleozoic volcanic rocks are widespread in northwestern Nevada, their total outcrop area is very small, and the basement rocks for these volcanic rocks is essentially unexposed or unrecognized (Figure 27), except in the Jackson Mountains, where volcanoclastic sedimentary rocks of the McGill Canyon succession are exposed (Russell, 1981). The McGill Canyon succession consists of volcanoclastic rocks interbedded with calcareous and siliceous sedimentary rocks that yield fossils of Devonian or Mississippian to Leonardian age. Because of the difficulty in studying rocks of Sonomia, it is unknown whether all exposures are part of the same arc or comprise a composite terrane.

There are important differences between the Late Permian deformation

Figure 27: Rocks of Sonomia. After Speed (1979).

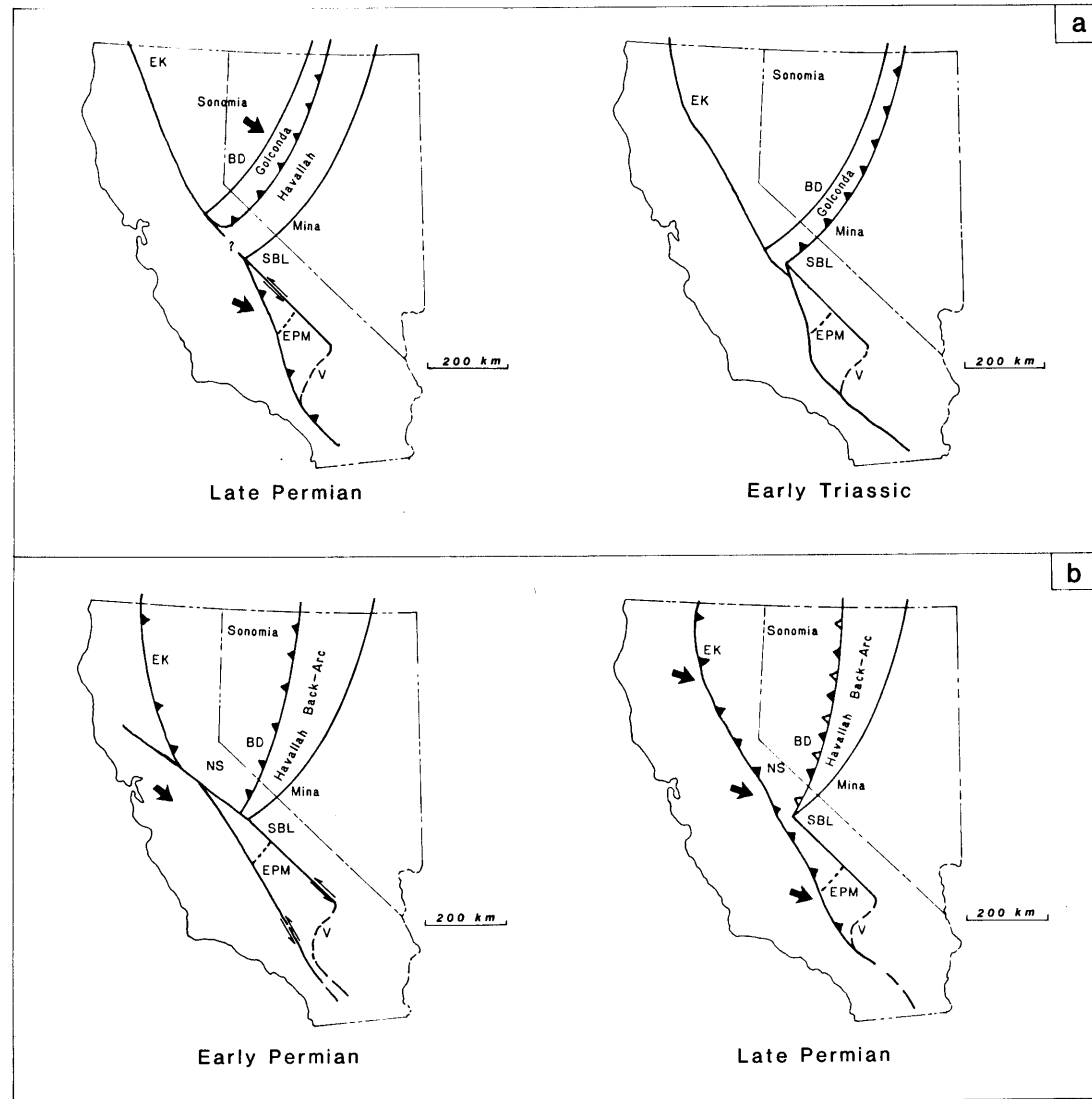


in the Mojave and that associated with the Permo-Triassic Sonoma Orogeny. Deformation of the continent is younger in the Sonoma belt than in the Mojave. Metamorphism and voluminous igneous activity accompanied deformation in the Mojave, whereas deformation in the Sonoma belt was not associated with metamorphism or with significant igneous activity. The reason for this difference seems to be that in the Mojave, subduction occurred under the continental margin whereas in Nevada the continental margin itself was the downgoing plate.

Several plate-tectonic models for the development of the western United States in Permian and Triassic time have been presented by Speed (1978, 1979), Schweickert and Snyder (1981), and Saleeby (1981). None of them is consistent with relations in the Mojave Desert. Figure 28 shows two geometries for the Permo-Triassic development of the western United States that are more compatible with the new data for California. The two interpretations differ mainly in the size and significance of the Havallah basin. Figure 28a is modified from Speed (1979). In this model, the Havallah basin is a large oceanic basin and the Golconda Allochthon represents an accretionary prism of Havallah rocks scraped up in front of the Sonomian arc. Subduction is divided and is beneath both Sonomia and southwestern United States.

In Figure 28b, the Havallah basin is interpreted to have been a relatively small back-arc basin, along the lines suggested by Miller and others (1984). In this scenerio, subduction is east-directed under Sonomia and the Mojave. Hence, the arc is of Alaskan type, and deformation of the Havallah sequence is mainly Late Permian. This model would also imply that some thrusting of rocks of the Golconda Allochthon could have occurred later. This model places the Sierra Nevada and Eastern Klamath arc

Figure 28: Options to plate tectonic evolution of the western United States in Permian and Early Triassic time. Figure 28a is after Speed (1979). Figure 28b does not include the Early Triassic but it is similar to Figure 28a.



sequences outboard of continental North America. The possible doubling of arc sequences in the Sonomia and Eastern Klamath area would be the result of later Mesozoic strike-slip faulting. The age of this duplication is poorly constrained, but can probably be assigned best to Medial and Late Triassic time because, significant dextral deformation of this age seems to be important in the Sierra Nevada (Saleeby, 1981). This would provide a mechanism for cooling of the Sonomia arc to commence, leading to subsidence, with associated stretching, of the arc to form the Late Triassic basin in western Nevada (Speed, 1978).

Two extreme views can be taken on the relation of the Sierra Nevada and Klamath Paleozoic magmatic arcs to North America. One holds that the Sierras and Klamaths are entirely exotic and were not near North America until Mesozoic time. However, many authors have correlated rocks in Sonomia, the Sierras, and the Klamath Mountains based on their similar lithology and faunal assemblages (Schweickert, 1976, 1981; Speed, 1979; Ross and Ross, 1983). One problem in making reconstructions of Sonomia is the faunal affinities of this block. Ross and Ross (1983) and Stevens and Rycerski (1983) interpret the Permian fauna of these areas to represent deposition at low latitudes to the south of the western United States and/or with large longitudinal separation. There is some suggestion that the Klamath Mountains shared fauna with the El Paso Mountains and Inyo Mountains in Early Permian time (Magginetti, 1984; Ross and Ross, 1983, p. 12), so large separations may not be implied. However, C.H. Stevens (oral communication, 1985) asserts that these correlations cannot be supported. In any case, the position of these rocks with respect to North America remains uncertain.

CHAPTER 7: Structural Problems

General Structural Problems

In this chapter I review the general structural development of the Mojave Desert from late Precambrian to Recent time. This review will include details of the nature of the larger-scale motions connected with late Paleozoic continental truncation, the Mojave-Sonora megashear hypothesis, and the internal deformation in the Mojave Desert, which affects the positions and trends of the various paleogeographic elements. The structural development of this area has important consequences for evolution of the boundary between in-place miogeoclinal and displaced eugeoclinal sequences, and how it was modified in Mesozoic and Cenozoic time.

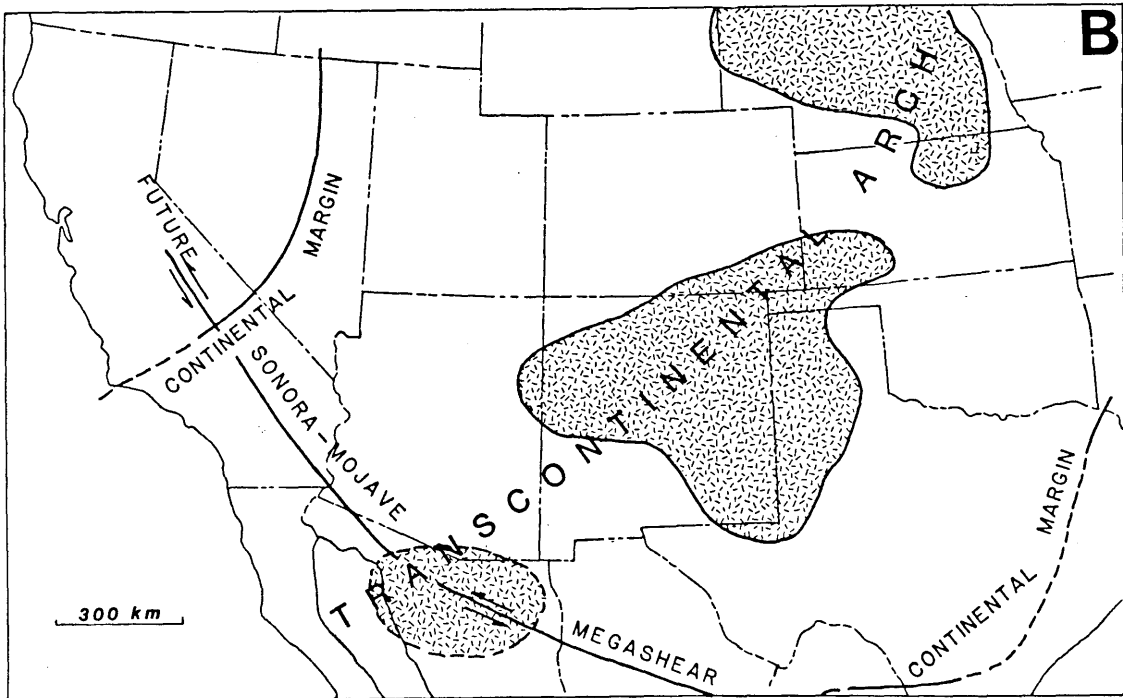
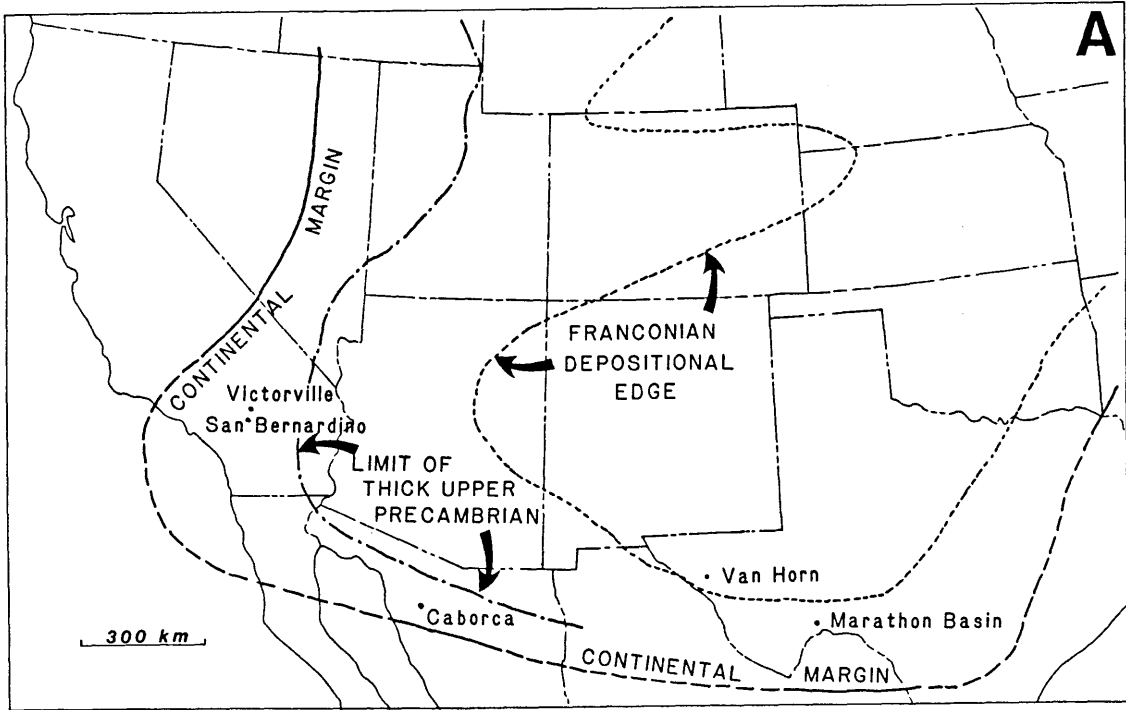
We have no good control on how far the continental margin and North American craton continued southwest of the Mojave Desert in Paleozoic time, or the extent of material removed during the truncation event in late Paleozoic time. The Mojave Desert has consistently been very close to the edge of the continental margin from late Paleozoic time onward because:

- 1) it is the only area where Late Permian deformation affected the craton;
- 2) the area was affected by Permian and Mesozoic plutonism, while other areas of similar Paleozoic paleogeographic affinities escaped unscathed;
- and 3) the Mojave is currently being truncated now by movement on the San Andreas Fault.

One feature that could aid in determining how far the continental margin continued southwest of the Mojave Desert is whether the miogeocline and rifted belt of the Cordilleran system wrapped around the Mojave Desert and continued into the Ouachita belt, or if the two belts were always isolated (Figure 29A,B). Stewart (1981a, 1982; Stewart and others, 1984)

Figure 29: Options for the relationship of the Cordilleran and Ouachita continental margins in early Paleozoic and late Precambrian time. Figure in part after Stewart (1982).

- A: continental margin is placed at the shelf edge. The limit of thick upper Precambrian corresponds to the limit of well-developed, Death Valley type sections. In this model, the Caborca rocks and western Mojave rocks are in place.
- B: Separate Cordilleran and Ouachita belts. Southwestern exposure of Precambrian crystalline rocks on the Transcontinental Arch is hypothetical. In this model, the apparent connection of the Cordilleran and Ouachita belts occurs across a low on the Arch, and Caborca rocks are displaced by the Sonora-Mojave megashear.



have addressed this problem, and a brief summary of relevant data is given here. Basic to this question is whether rocks in the Caborca area and south in Sonora, Mexico, are in place or displaced relative to the Cordilleran and Ouachita belts. Upper Precambrian and Cambrian rocks near Caborca have miogeoclinal affinities (Stewart and others, 1984, p. 25-28, 30). Rocks to the south have eugeoclinal affinities (Stewart, 1981b; Poole, 1981), and apparently were deformed in Devonian-Mississippian time. However, upper Paleozoic and lower Mesozoic rocks at El Capitan (northwest of Caborca) have cratonal affinity (Leveille and Frost, 1984). Palmer and others (1984) presented data that suggest that the southern Ouachita continental margin was south of the Marathon Basin area of Texas and the southern edge of the inner (cratonal) zone of the Ouachita belt was south of the Van Horn area and continued westward into southern Arizona. These data indicate that rocks in the Caborca area may be relatively in place, although probably telescoped, and that the Ouachita margin trended westward through the southern United States and northern Mexico to connect with the Cordilleran belt (Figure 29A). This interpretation would imply that a single continental margin wrapped around the Mojave desert and connected the Ouachita and Cordilleran belts. In this model, the Mojave would have formed a promontory established during late Precambrian rifting (as suggested by Dickinson, 1977); the corner of this promontory was removed during late Paleozoic continental truncation.

Alternatively, because the connection of the Ouachita belt into northern Mexico is still only an interpretation, the Ouachita and Cordillera belts may have formed as completely separate continental margins (Figure 29B). Also shown in Figure 29B is a hypothetical continuation of the crystalline basement rocks of the Transcontinental Arch. In this

model, the apparent connection of the Ouachita and Cordilleran belts would occur across a basement low on the Arch. Rocks of the Caborca area may have been displaced southward to their present position from the Cordilleran belt during late Paleozoic truncation or later Mesozoic faulting. Caborca strata have facies similar to those of the Death Valley and San Bernardino Mountains (Stewart and others, 1984, p. 26). This feature has been long recognized, and has led various authors to suggest that the Caborca rocks may be displaced from north in the Cordilleran belt during late Paleozoic time (Cameron, 1981; Burchfiel and Davis, 1981), or Mesozoic time, (Silver and Anderson, 1974). If the Caborca rocks are indeed displaced from the north, then movement must have occurred prior to Mesozoic time, since Triassic rocks in the Caborca area and to the south are unlike rocks in the San Bernardino Mountain area and northward. The original position of the the Caborca rocks, either in place or displaced, would further constrain the location of the late Paleozoic truncation boundary: if Caborca rocks are displaced, then these rocks have probably been juxtaposed together with cratonal rocks during late Paleozoic truncation and later Mesozoic deformations; if in place, then the truncation boundary must be located southwest of Caborca.

In part, how we interpret the relative positions of rocks in the western United States and Mexico depends on which paleogeographic trends we consider most diagnostic of their original positions. In this study, I have principally used trends in Paleozoic rocks, because they best define the miogeocline and record structural and tectonic elements, such as the Roberts Mountain Allochthon and Antler belt. Isopachs and facies distributions of upper Precambrian rocks must be used with caution, because tectonism related to rifting occurred during their deposition

(Christie-Blick, 1984). On a Cordilleran-wide scale, upper Precambrian strata probably reflect the trend of the continental margin well, but on smaller scales they may only reflect structures of local significance. Therefore, I assume that paleogeographic trends defined by Paleozoic strata best record the overall geometry of the continental margin in the Death Valley area and the Mojave Desert. Late Precambrian trends, such as those oriented north-northwest in the northeast and eastern Mojave Desert (Figure 1; Stewart, 1970), probably record important late Precambrian to Early Cambrian rift-stage features, but not the final drift-stage configuration of the continental margin.

Another interpretation of the rocks in the Caborca area is that they were displaced from the Death Valley area in Middle Jurassic time along a hypothetical strike-slip fault called the Mojave-Sonora Megashear, first named by Silver and Anderson (1974; further elucidated by Anderson and Silver, 1979, and Anderson and Schmidt, 1983). The proposed location of this fault is shown in Figure 29B. Net offset on this fault is considered by Silver and Anderson to be 700 to 800 km based on matching rocks in the Caborca area with strata in the Death Valley area, and on mismatch of Precambrian crystalline basement rocks across Sonora and southern United States (Figure 29). There are several problems associated with the megashear hypothesis. First, Leveille and Frost (1984) documented the presence of North American rocks of cratonal facies which form the logical continuation of the cratonal belt in Arizona, on the southwestern, e.g., displaced, side of the megashear. Second, the trace of the megashear as proposed by Silver and Anderson passes through the center of the Mojave Desert. Cameron (1981, 1982) noted that such a path is very unlikely since cratonal and miogeoclinal rocks are continuous across the Mojave. Lower

Triassic strata are also continuous across the proposed megashear. However, Silver (1982) proposed that rocks in the Victorville and San Bernardino Mountain areas were thrust into their present position across the megashear from the eastern Mojave. Evidence for this thrusting event is lacking in the western Mojave, and the tie of in-place and displaced rocks in the Mojave in Early Triassic time probably precludes such thrusting. Finally, if movement on the megashear occurred in post-Early Jurassic time as proposed by Silver and Anderson, then serious mismatches of Mesozoic facies are created: Upper Triassic and Lower Jurassic rocks southwest of the megashear in the Caborca area and southward are unlike any found in the Mojave Desert or Death Valley area.

In actuality, the only rocks demonstrably offset along the Silver-Anderson megashear are Proterozoic crystalline basement terranes, one dated at 1.7 to 1.8 Ga, the other at 1.6 to 1.7 Ga. This offset only implies a lower age limit of 1.6 Ga for faulting. An upper age limit is more difficult to assess. If Triassic and Paleozoic rocks are continuous from Arizona to El Capitan, then megashear activity is best assigned to late Precambrian time. Eisbacher (1981, p. 20) and Walker and others (in preparation) consider transcurrent faulting to be an important part of the late Precambrian evolution of the Cordillera. Hence, offset of Proterozoic basement terranes in Mexico and southern United States may have occurred during rifting of the continental margin. It is also possible that the trace of the megashear does not cross the Mojave Desert as proposed by Silver and Anderson, and that it actually passes to the south of the San Bernardino Mountains, and rocks in the Caborca area are derived from south or west of the San Bernardino Mountains. If this is correct, then offset would must have occurred before Late Permian time, since the

Caborca sections show no evidence of Late Permian arc activity. Regardless of which interpretation is favored, two important points concerning the megashear are: 1) the trace of the megashear cannot go through the central Mojave Desert; and 2) movement must have occurred prior to Late Permian time.

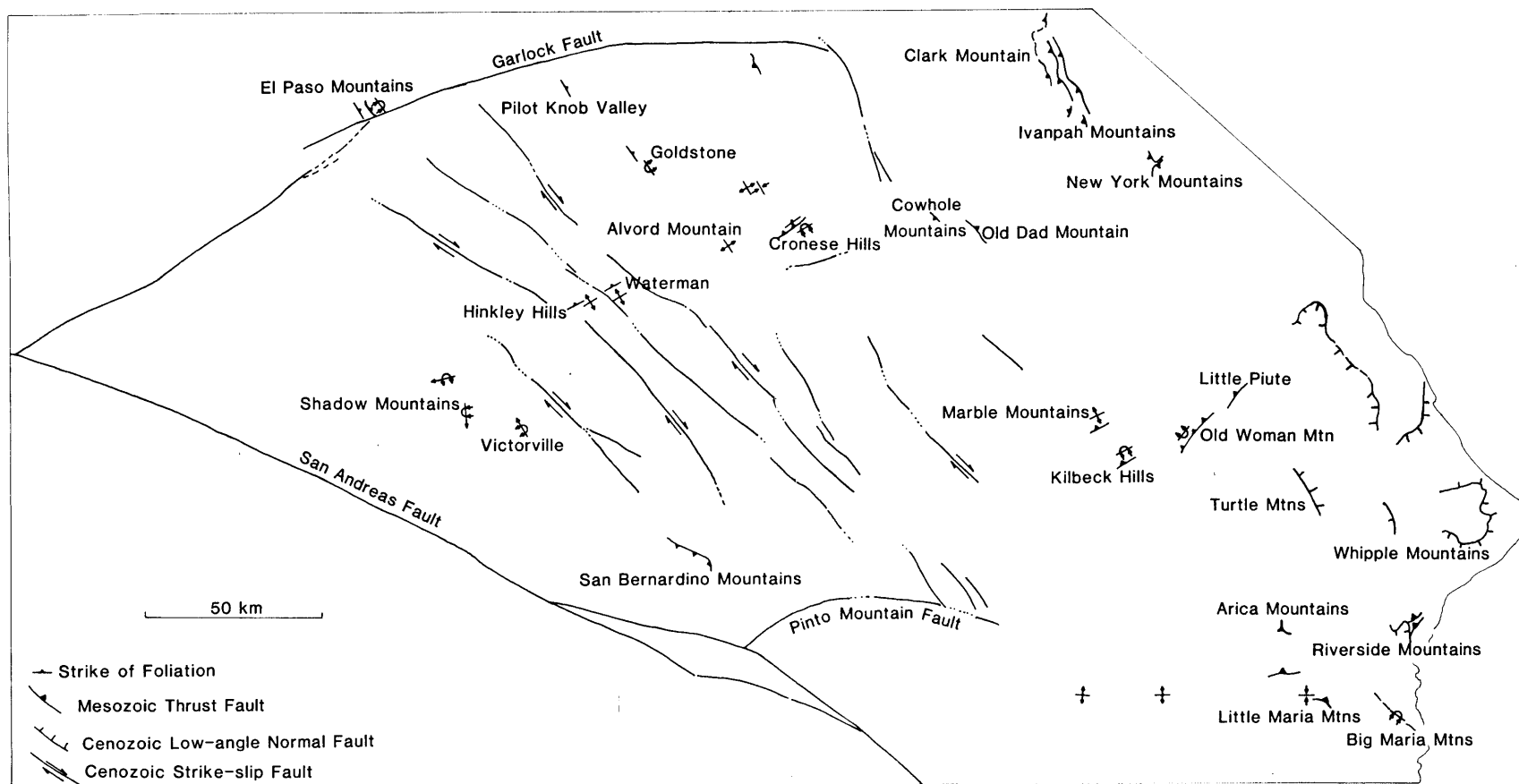
Part of the reason for proposing a fault like the Mojave Sonora megashear is to explain space problems associated with the Jurassic opening of the Gulf of Mexico (Dickinson and Coney, 1980; Anderson and Schmidt, 1983). However, the geology of the Mojave Desert and Death Valley area is sufficiently well understood to preclude movement on a fault like the megashear; on the other hand, the geology of Mexico is still so poorly known as to allow major revisions of the megashear hypothesis. Further work will certainly resolve many of the problems presented above.

Deformation of the Mojave Desert

Understanding the internal deformation of the Mojave Desert is important to determine the changes in the shape and the trend of paleogeographic and structural features. In discussing the structural development of the Mojave, I will start with the youngest events in the Mojave and work backwards in time and complexity.

The latest structures in the Mojave Desert are Miocene to Recent age, northwest-trending strike-slip faults (Figure 30). Dokka (1983) has presented the most recent and most accurate interpretation of displacement on these faults. Dokka estimated a cumulative displacement of 26.7 to 38.4 km on the faults across the Mojave. This amount of movement would result in about maximum 10° rotation in the Mojave, e.g., northeast-trending structures and facies boundaries would be rotated about

Figure 30: Principal structures in the Mojave Desert. Data from E.L. Miller (1981), Burchfiel and Davis (1971, 1977, 1981), Miller and Sutter (1982), M.D. Carr and others (1984), Brown (1983), Troxel and Gunderson (1970), Cameron, (1981), Emersom (1982), Lyle (1982), Hamilton (1982), Baltz (1982), C.F. Miller and others (1982), Davis and others (1980), Bowen (1954), Kiser (1981), McCulloh (1952), and Byers (1956).



MAJOR STRUCTURES - MOJAVE DESERT

10° clockwise. Dokka's interpretation is conservative compared to that of Garfunkel (1974), who assumed about 30° or more clockwise rotation and cumulative offset of 65 to 105 km on the Tertiary strike-slip faults. I favor Dokka's interpretations and will use them in reconstructions.

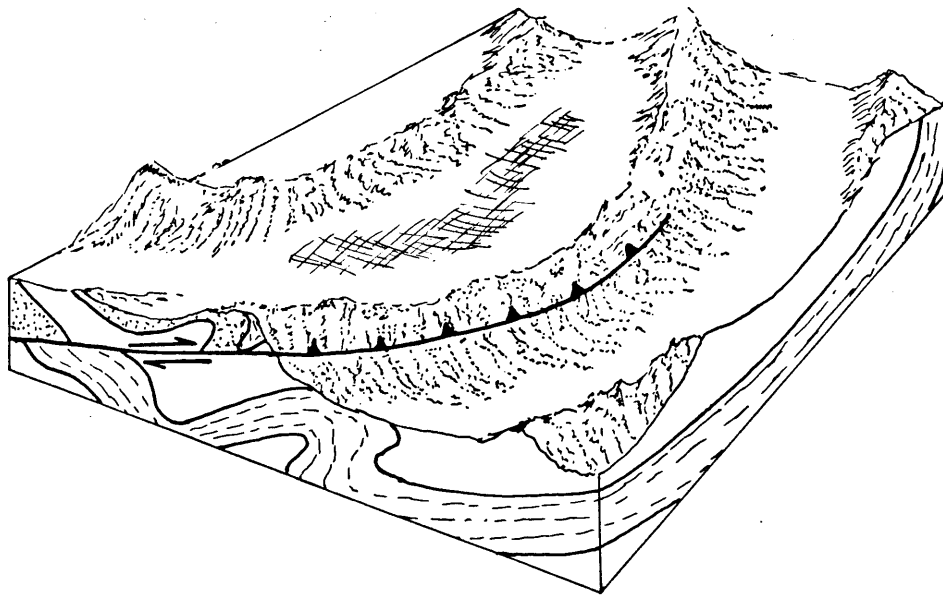
A period of low-angle normal faulting, with syntectonic sedimentation and volcanism, preceded the strike-slip faulting in the central (Dokka and Glazner, 1982) and eastern Mojave Desert (Davis and others, 1980). Extension in the central Mojave is bracketed between 20 and 23 Ma (Dokka and Glazner, 1982, p. 36-37), and may be somewhat younger to the east. The magnitude of extension in the central Mojave is poorly constrained, but is probably on the order of tens of kilometers in the east.

Mesozoic deformational structures can be divided into two dominant sets: 1) southeast-vergent to south-vergent structures in the eastern and southeastern part of the Mojave Desert (Emerson, 1982; Lyle, 1982; Ellis, 1982; Howard and others, 1980; Howard, 1981; and C.F. Miller and others, 1982); and 2) east-directed structures in the northeastern corner of the Mojave Desert (Burchfiel and Davis, 1971, 1977). South-directed thrusts are present in the Cave Mountain and Cronese Hills area. These structures are considered to be synkinematic with Middle Jurassic plutonism and metamorphism (B.C. Burchfiel, oral communication, 1984). Late Permian and Permian (?) deformation is present in the Victorville area and the San Bernardino Mountains, and consists of east-vergent folds and thrusts faults (E.L. Miller, 1981; Cameron, 1981). Overall shortening on late Paleozoic and Mesozoic structures is inferred to be minor. Lateral continuity of all structures is poorly understood, and reconstructions of the deformed region prior to tectonism are very speculative. However, I consider most of the compressional structures described above to have had little effect on the

relative geometry of paleogeographic trends in the Mojave (as we understand the structures at present), although faults in the Cave Mountain and Cronese Hills areas may have major consequences (see below).

Albers (1967) proposed that a major component in the configuration of a portion of western Nevada and eastern California was right-lateral oroclinal bending (Figure 31). This zone of bending is reflected in the patterns of structures (faults and folds), isopachs, and trends in mountain-range morphology. Total displacement of 130 to 200 km about the oroclinal axis was proposed by Albers. Speed (1978, p. 267-268) assigns movement mainly to Jurassic time, and Albers (1967) favors Jurassic and Cretaceous bending, but also considered some of the bending deformation to be Tertiary (but pre-Miocene). If this much displacement occurred in western Nevada and eastern California, effects should be present in the Mojave Desert. There may be structures in the Mojave that record such bending. South-vergent faults and folds in the eastern Mojave are anomalous to the Cordillera as a whole both in orientation and structural style. However, these structures might result from deformation around the nose of an oroclinal bend, much as in the manner suggested by Albers (1967, p. 147). In addition, some apparent bending and stratigraphic reorientation in the Great Basin is certainly the result of Cenozoic strike-slip faulting (Stewart, 1967), although the interaction of oroclinal bending and faulting is far from clear. Major strike-slip faults are the Furnace Creek-Death Valley fault zone, Las Vegas Valley Shear Zone, and the Walker Lane area. Cenozoic displacement on these faults may lower the amount of Mesozoic bending required to straighten out trends by as much as 70 km.

Figure 31: Structures associated with oroclinal bending (after Albers, 1967). Note thrust faults and folds produced around the nose of the bend (upper diagram). South-directed structures in the eastern Mojave Desert could be related to such bending. Similar structures are also present to the east in Arizona.



Oroclinal Bend

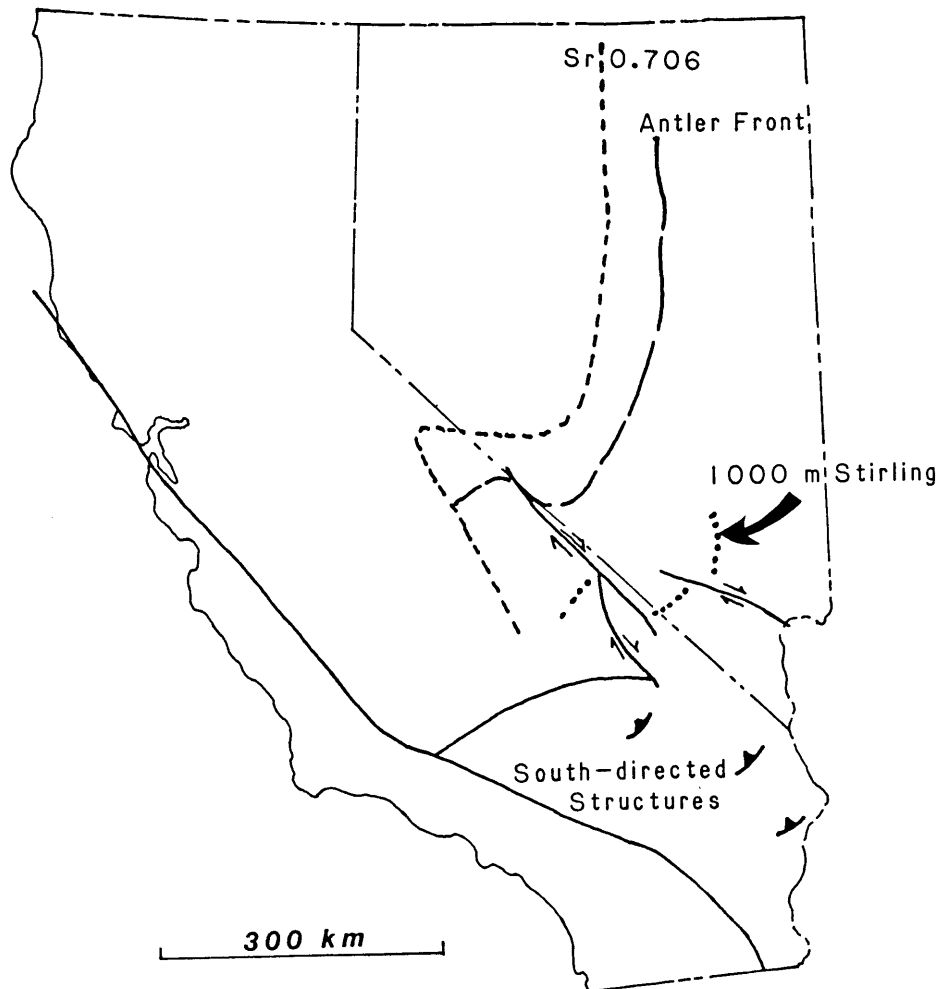
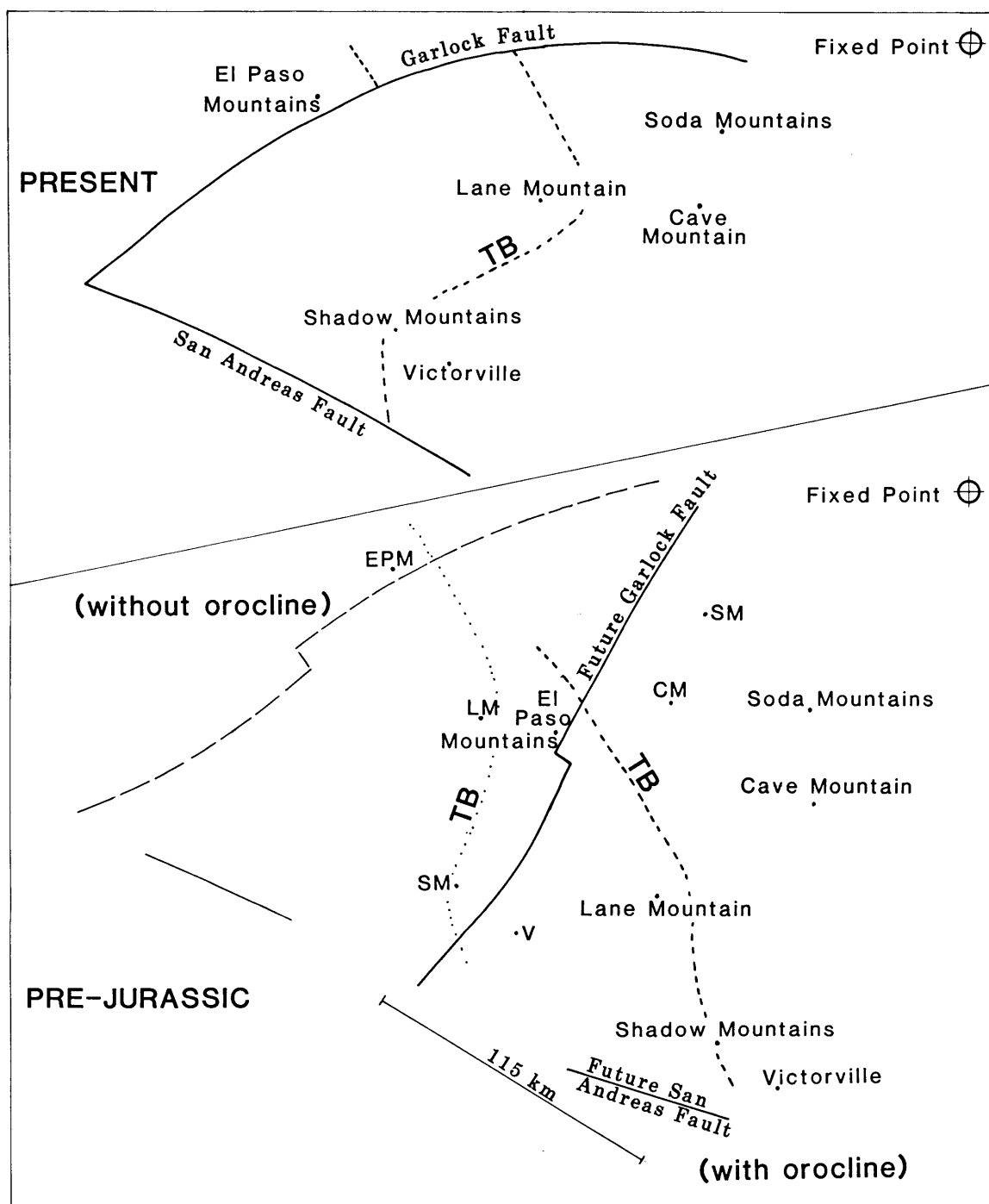


Figure 32 is an attempt to restore the Mojave Desert to its pre-Mesozoic configuration. I have retained the traces of the Garlock and San Andreas faults for reference, as well as the locations of many areas of interest in this study. This reconstruction should be viewed as very approximate. Note that the line separating displaced and in-place rocks is much straighter and more north-south trending in this reconstruction.

This reconstruction prepares us to discuss the modification of the boundary between in-place miogeoclinal and displaced eugeoclinal rocks. The boundary presently runs south-southeast from west of the Saddlebag Lake Pendant south to a point between the El Paso Mountains and Slate Range, where it is offset to the east on the south side of the Garlock Fault. From there it turns west-southwest and follows a circuitous path across the Mojave. Even when rotations and deformation reviewed above are reversed, the path is far from straight and regular. It is possible that its original trace was curved; alternatively, other important structures have not been considered properly that could modify its shape and position.

In the Cave Mountain and Cronese Hills area there is important Middle Jurassic shortening and metamorphism. Structures juxtapose metavolcanic, metasedimentary, and metaplutonic rocks along thrusts dipping about 30° to north-northwest. Folds trending northeast and verging southeast were also formed in this event. Similar structures form a zone of deformation that apparently continues westward into the area of the Waterman Gneiss complex and the Hinkley Hills (Figure 4; Kiser, 1981; Bowen, 1954, p. 95-97), and roughly coincides with the present boundary of in-place and displaced rocks. The middle Jurassic (?) structures seem to continue into the Shadow Mountains and Victorville area, where deformation is in part Late Permian. This implies that there may be multiple periods of deformation in these

Figure 32: Reconstruction of the Mojave Desert. Upper diagram is the present configuration. Lower diagram shows reconstructs both with and without removing about 115 km of simple shear deformation across the area. TB: truncation boundary.



areas, and that only the latest stage has been clearly identified. Exposures of presumed Precambrian rocks to the north of this belt in the Fremont Peak area (Dibblee, 1968) may indicate that overthrusting and reshuffling of displaced Roberts Mountain Allochthon rocks occurs over a width of 20 to 50 km (or more). However, many of the presumed Precambrian rocks are in the Waterman Gneiss complex and are still undated. It is possible that the complex is composed of highly deformed and metamorphosed upper Precambrian or Paleozoic rocks of miogeoclinal or eugeoclinal affinities. The presence of marble horizons in the Waterman Gneiss (Bowen, 1954; Dibblee, 1968) may point toward a Paleozoic age for the protolith of these rocks, since carbonate is rare in other dated Precambrian rocks in the Mojave Desert. Rocks in the Hinkley Hills have been correlated with North American miogeoclinal rocks (Kiser, 1981).

Hence, there is evidence that the late Paleozoic truncation of eugeoclinal and miogeoclinal rocks has itself been overprinted by Mesozoic deformation. At present, there is no recognizable structural feature in the Mojave Desert that can be assigned to the truncation event; it is apparently completely overprinted by later deformation.

Burchfiel and Davis (1981) and Davis and others (1978) identified two truncation boundaries. The inboard one, the one closest to the continent, bounds miogeoclinal rocks to the east and displaced Roberts Mountain Allochthon rocks to the west: this feature has been the focus of this thesis. The outboard truncation is responsible for removing the extension of the Antler belt. Saleeby (1981) called for extensive transcurrent faulting along the western continental margin throughout Mesozoic time, and presented evidence for removal of North American material. This suggests that the original outer truncation envisioned by Burchfiel and Davis has

been overprinted, and may not be anywhere preserved as a single feature.

In summary, deformation has occurred in the Mojave Desert repeatedly since the late Paleozoic truncation event, and the original structural geometry of the truncation cannot be uniquely retrieved from the present structural configuration. Events involving thrusting and bending in Jurassic time have affected the trend and position of the truncation. Cenozoic extensional and strike-slip faults have further changed the geometry of the truncation. The overprinting, which obscures the truncation boundary and makes its interpretation more difficult, does not negate the need for a truncation, because the truncation is based on well established stratigraphic and tectonic grounds.

CHAPTER 8: Conclusions

Lower Triassic rocks extend from the eastern Mojave Desert, where they correlate with the Moenkopi Formation of the Colorado Plateau, into the western Mojave Desert, where they overlie deformed transitional-cratonal facies rocks and Upper Permian plutonic rocks in the Victorville area and probably Upper Permian Volcanic and lower Paleozoic eugeoclinal rocks in the northwestern Mojave Desert. Eugeoclinal rocks were displaced southward from the Antler belt, and Lower Triassic rocks comprise an overlap sequence for juxtaposition of the eugeoclinal rocks with transitional-cratonal rocks of the Mojave and for deformational events of Late Permian age.

The trend and paleogeographic and tectonic settings of the Cordilleran continental margin changed in late Paleozoic time. The margin trended northeast-southwest across the Mojave Desert and the Basin and Range Province during late Precambrian to Mississippian time, but apparently changed to roughly north-south in late Paleozoic time. The tectonic setting became one of a continental borderland, from a previously passive margin modified by the Antler Orogeny, in Pennsylvanian and Early Permian time. Eugeoclinal rocks of the Antler belt were apparently displaced southward to their present relative position in the northwestern Mojave Desert during this event. In Late Permian time, subduction began under the new margin; evidence of this event is recorded by deformation and magmatic arc development in the Mojave Desert.

Marine Lower Triassic rocks were deposited across all older rock assemblages during a lull in magmatic-arc activity. Sedimentation was shallow-marine to nonmarine in character in the eastern Mojave and follows source and depositional patterns that were prominent throughout Paleozoic

time. To the west, depositional trends interpreted from Lower Triassic sequences follow new, northwest-southeast directions. Deposition was in marine to nonmarine basins; abundant locally derived conglomerate attests to the creation of relief in Late Permian time and possible relief in Early Triassic time related to faulting.

The Lower Triassic rocks apparently record the final presence of a marine basin in the western Mojave Desert. In Middle Triassic time the magmatism arc became active, and volcanism extended across most of arc Mojave Desert. The arc extended northwestward into the Basin and Range and possibly southwestward into Arizona.

Lower Triassic rocks are post tectonic after deformation and plutonism in the western Mojave Desert, but are apparently pretectonic to syntectonic to Sonoma Orogeny deformation as they are traced northward into western Nevada (Mina area) and eastern California. The Sonoma Orogeny clearly postdates deformation in the western Mojave Desert, and is nonmetamorphic and unaccompanied by plutonism, in contrast to the Mojave Desert.

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APPENDIX A

Revised Geology and Stratigraphy of a
Part of the Soda Mountains,
Northeastern Mojave Desert, California

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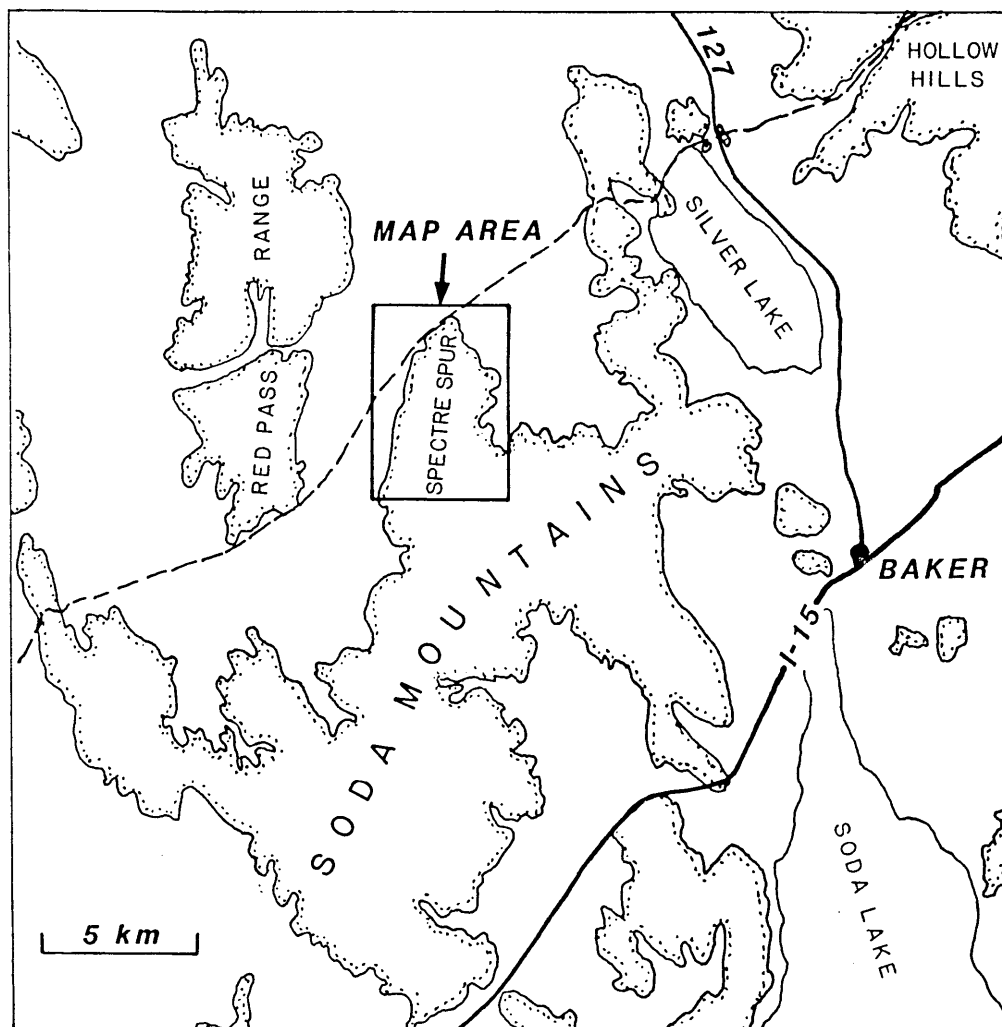
Introduction

This report describes the stratigraphy and structural evolution of a part of the Soda Mountains in the eastern Mojave Desert, California (Figure 4; 33). Grose (1959) mapped the entire Soda Mountains and recognized many of the important rock units and geologic structures in the area. Stewart (1970) reexamined and correlated upper Precambrian rocks in the Soda Mountains with similar units in the Death Valley area. Burchfiel and others (1980) reported a new exposure of probable Triassic rocks in the north-central Soda Mountains, and correlated them with similar strata to the north and west.

It was the discovery of the probable Triassic rocks which prompted the present investigation. The work of Miller (1981), Burchfiel and others (1980), and Cameron and others (1979) has shown that there was significant Permo-Triassic deformation in the Mojave Desert and that the study of early Mesozoic strata helps to constrain the timing and extent of this deformation. This investigation of the Soda Mountains was made to better establish the age and distribution of probable Triassic rocks and to determine whether underlying Paleozoic strata were deformed prior to deposition of the Triassic rocks. Restudy of the Soda Mountains revealed a wide distribution of Lower Triassic sedimentary rocks, a previously unrecognized sequence of Cambrian to Pennsylvanian strata, and Lower Permian rocks in distinctive turbidite facies; the correlation of these rocks also helped to reinterpret and remap structures in the area.

The study centered on the Spectre Spur area of the Soda Mountains (informal name applied by Grose, 1959). Plate 3 is a geologic map of the study area. Field mapping was done on a topographic base at a scale of 1:10,560. Names used for Paleozoic units are those recognized in the

Figure 33: Location map of Spectre Spur in the Soda Mountains. For other locations see Figure 4.



literature for eastern California. A measured section of the Early Triassic rocks is presented and a new name and type section is proposed.

Regional Geologic Setting

The Soda Mountains lie near the hinge line of the Cordilleran Miogeocline: thick and mostly complete sections of Paleozoic strata are present to the north of this area and thin and abbreviated sections to the south. In the Avawatz Mountains to the north and at Old Dad Mountain to the south, Devonian rocks rest on Cambrian rocks and record a widespread Siluro-Ordovician hiatus in Cordilleran platformal sedimentation (Spencer, 1981). Deposition in the miogeocline become two-sided in Mississippian time following the Antler orogeny, but westward-derived material is not present in the Soda Mountain area (Poole, 1974).

Further reorganization of the continental margin began in Pennsylvanian time when the shelf-slope break changed trend in east-central California (Stone and Stevens, 1984). Effects of this event are present as far south as the Soda Mountains and the eastern Mojave Desert (Stone and Stevens, 1984; Walker and others, 1984; Stevens, 1982), and are recorded by subsidence accompanied by deposition of turbidites onto formerly shallow-water shelf areas, and changes in faunal distributions. Reorganization is thought to have occurred in a borderlands/strike-slip-faulting setting (Stone and Stevens, 1984).

Deformation of upper Precambrian and Paleozoic strata and development of a magmatic arc occurred in the western Mojave Desert in Late Permian time (Carr and others, 1981; Burchfiel and Davis, 1981; Burchfiel and others, 1980). Structures developed during this event are thought to

extend to the central Mojave Desert and possibly into the Soda Mountains (Burchfiel and others, 1980; Cameron and others, 1979). Deformed Paleozoic sections and Upper Permian plutonic rocks are overlain by Lower Triassic and probable Lower Triassic rocks which are equivalent to cratonal sequences to the east in southern Nevada and Arizona (Walker and others, 1984; Burchfiel and others, 1980). Magmatic arc activity resumed in Middle Triassic time and migrated as far east as the Soda Mountains and adjacent areas.

Stratigraphy

Pre-Tertiary rocks in the Spectre Spur area range from the Cambrian Nopah Formation to Cretaceous hypabyssal intrusive rocks. Descriptions of these units are given below. Grose (1959) did not recognize or correctly correlate many of the Paleozoic and Early Triassic rocks in the Soda Mountains because of the effects of Mesozoic deformation and metamorphism. We were aided in deciphering the stratigraphy of Spectre Spur by advances in understanding of stratigraphy of eastern California (many of which were made subsequent to Grose's work in the area) and by using conodonts for biostratigraphic control. Not all units are directly dated, however, and many are assigned ages based on lithology and stratigraphic succession.

Nopah Formation

Rocks assigned to the Nopah Formation, exposed on the western flank of Spectre Spur, consist of light-gray to cream-colored, medium-grained dolomitic marbles. Banding defined by centimeter-scale layering is present; it results from ductile transposition of the unit and does not represent original bedding. In the more deformed and thicker sections,

minor calc-silicate rock and darker gray dolomitic marble horizons are included in this unit, but may represent the Dunderburg Shale Member of the Nopah Formation and/or the Bonanza King Formation. These rocks are correlated with the Nopah Formation based on their similarities with metamorphosed Nopah Formation in the Avawatz Mountain (Spencer, 1981). Grose (1959, p. 1518-1519) assigned these rocks to his Mississippian-Pennsylvanian (?) limestone unit.

Sultan Limestone

The Sultan Limestone in the Soda Mountains consists of a lower unit of light-gray and dark-gray banded dolomitic and calcitic marble and an upper unit of calcitic marble. Although it was not subdivided in the Soda Mountains, the lower unit is probably equivalent to the Valentine Member and the upper unit to the Crystal Pass Member of the Sultan Limestone as it was first described by Hewett (1931). Minor calc-silicate horizons present in the upper part were probably derived from chert; one or two cherty layers are present in the uppermost Sultan Limestone in areas east of the Soda Mountains.

Monte Cristo Limestone

Rocks assigned to the Monte Cristo Limestone are exposed on the west and east (?) flanks of Spectre Spur. Strata on the west flank is best preserved, and three members are recognized: the lowest consists of medium-grained, gray-weathering to brown-weathering marble that is assigned to the Dawn Member; the middle member comprises gray calcitic marble with abundant calc-silicate segregations and is correlated with the Anchor Member; the upper member consists of medium-grained, light-gray calcitic

marble and is assigned to the Bullion Member. Isolated and deformed crinoid stems and corals are locally present in the Bullion Member. However, the fossil material is too poorly preserved to be diagnostic. Grose (1959) included Monte Cristo Limestone in his Mississippian-Pennsylvanian (?) limestone unit.

Bird Spring Formation

Rocks correlated with the Bird Spring Formation crop out on the east and west flanks of Spectre Spur, and are best preserved in their stratigraphic context on the west side. The Bird Spring Formation consists of thin-bedded to thick-bedded limestone and minor dolostone, calcitic and dolomitic marble, all of which locally contain abundant chert nodules, and sandstone. Solitary corals and crinoid stems were found but were not age diagnostic. Although this unit is not directly dated, it is correlated with the Pennsylvanian and Lower Permian Bird Spring Formation. Its lower contact with the Monte Cristo Limestone is placed at the transition from massive gray marble of the Monte Cristo Member into medium-bedded, light-gray and dark-gray marble of the Bird Spring Formation. The upper contact is gradational into generally thinner bedded carbonate rocks of the Permian Marble and calc-silicate sequence, and is placed arbitrarily where carbonate units become evenly and thinly bedded in beds 50-100 cm thick.

Permian Marble and Calc-silicate sequence

The marble and calc-silicate sequence is a newly subdivided unit consisting of thin-bedded to medium-bedded gray calcite marble and orange-weathering to brown-weathering calc-silicate hornfels exposed across the width of Spectre Spur. Many beds are internally graded from medium grained at their base to fine grained at top. Beds containing fusulinids

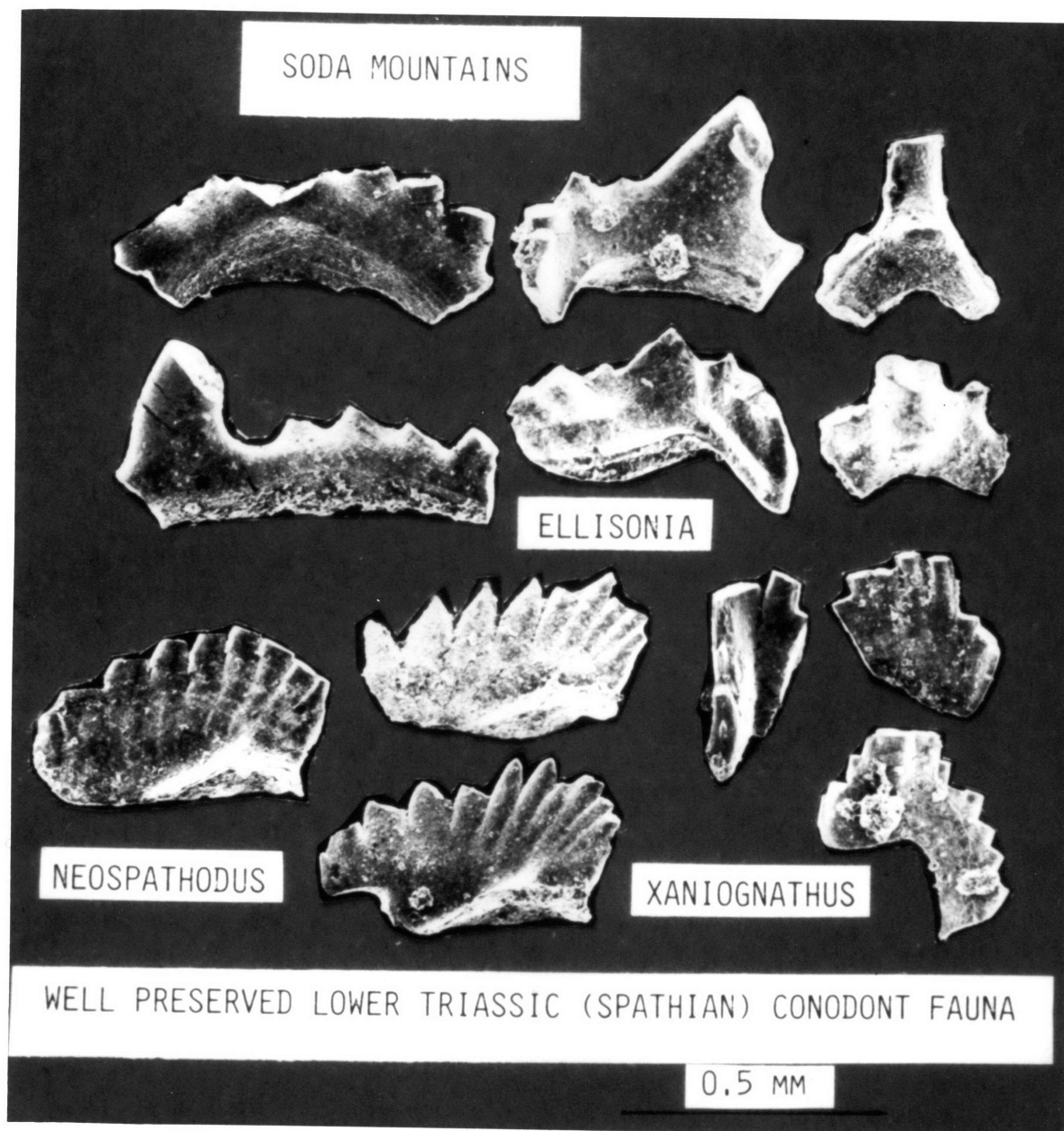
are locally present and are often graded. Many internal features of this unit are suggestive of deposition by turbidity currents: the common presence of graded bedding; the generally thin-bedded to medium-bedded nature of the unit; locally present convoluted bedding and medium-scale cross-stratification; and crude Bouma sequences, represented as calc-silicate horizons between graded clean limestone beds. Marble and calc-silicate rock are interbedded throughout the unit, but calc-silicate predominates at the top. The thickness of this sequence is unknown because of internal faulting and folding, but it is probably in excess of 1000 m.

Grose (1959) assigned these rocks both to his Mississippian-Pennsylvanian (?) limestone and hornfels unit and to the Lower Permian part of the Bird Spring Formation. However, these rocks constitute a single stratigraphic unit of Early Permian age. Grose recovered Schwagerina and Triticites from these rocks. We recovered the conodonts Xaniognathus and Neostreptognathodus Ruzhencevi (Kozur), indicative of late early Leonardian age, from two beds in the northern part of the area (Figure 34). These finds combined with Grose's data, imply an Early Permian age for the Marble and Calc-silicate sequence, although its lower age limit is not well established.

Silver Lake Formation

A sequence of Lower Triassic limestone, siltstone, and conglomerate, exposed in fault blocks on the northern end and on the crest of Spectre Spur, has been subdivided in the Soda Mountains. We propose the name Silver Lake Formation for this sequence, and present a detailed lithologic description, a measured type-section (included at the end of this section), and paleontologic data on these rocks.

Figure 34: Conodonts recovered from the Marble and Calc-silicate unit and the Silver Lake Formation.



The Silver Lake Formation consists of limestone, silty and iron-rich cherty limestone, siltstone, and conglomerate. These rocks are locally metamorphosed to marble and calc-silicate hornfels: rocks on the north end of Spectre Spur are better preserved, whereas those in fault slices on top of Spectre Spur are pervasively metamorphosed.

Siltstone is the most common rock type in the Silver Lake Formation. It is typically thinly laminated, but locally massive, and occurs in beds 20 to 100 cm thick. Internal structures include climbing-ripple lamination, small-scale cross-stratification, and parallel lamination. Cut-and-fill structure and mud cracks are also present but rare. The siltstone is quartz-rich; it is calcareous in the lower part of the unit but becomes iron-rich in the upper part. Limestone and silty limestone are the next most common rock types. Limestone is present as beds 50 cm to 5 m thick that are parallel laminated or massive. Chert is common as stringers and blebs up to 10 cm thick and 1 m long.

Conglomerate is present as lens-shaped beds typically 1 to 4 m thick, but locally on the top of Spectre Spur the beds are up to 10 m thick. Clasts range in size from pebbles to boulders (up to 50 cm in diameter) and are set in a sandy and silty matrix. Clasts include carbonate rocks, siltstone, chert, and rare metaplutonic and volcanic rocks. The carbonate and chert clasts were derived from underlying Paleozoic rocks. Gneissic plutonic clasts are inferred to have been derived from Precambrian crystalline basement rocks. Volcanic rocks were probably derived from areas to the west that were the site of Late Permian magmatic-arc activity.

The Silver Lake Formation rests unconformably on the Permian marble and calc-silicate unit. The contact is marked by about 60 cm of

distinctive black, thinly laminated limestone interbedded with pink siltstone. This limestone locally contains poorly preserved bivalves and other fossil debris. The upper contact is conformable with volcanic rocks of the overlying Soda Mountain Formation. In the northern exposures this contact is sharp; in the south the upper part of the Silver Lake Formation is a volcanoclastic metasiltite and metasandstone that is probably gradational into the Soda Mountain Formation although this cannot be established with absolute certainty because of faulting in the section.

Grose recognized the presence of Lower Triassic rocks in the Soda Mountain, but did not discover their lower contact with the Permian rocks or their full extent in the area. Our mapping and subdivision of the Silver Lake Formation was greatly aided by conodont dating and by advances in Great Basin stratigraphy since Grose did his work.

Age control on the Silver Lake Formation is provided by conodonts recovered from the lower half of the unit. Conodonts recovered consist of the taxa Ellisonia sp., Neospathodus Homeri (Bender), N. Triangularis (Bender), Xaniognathus sp., and Parachirognathis (?) sp.; these indicate that the Silver Lake Formation is of Spathian age. A sample of material recovered is shown in Figure 34.

Grose (1959, p. 1525) correlated rocks here assigned to the Silver Lake Formation with Lower Triassic rocks in the Inyo Mountains, Providence Mountains, and Butte Valley (Johnson, 1957; Hazzard, 1954). He also suggested that the Soda Mountain section might represent a westward equivalent of the Moenkopi Formation. Burchfiel and others (1980) correlated the Soda Mountain section with the Fairview Valley Formation near Victorville and the Bond Buyer sequence of the El Paso Mountains. We agree with these correlations, and propose the new name to emphasize

differences in lithology with the Moenkopi Formation to the east.

Soda Mountain Formation

Interbedded quartzite intermediate volcanic, volcanoclastic sedimentary, and hypabyssal intrusive rocks are assigned to the Soda Mountain Formation. The lithology and mineralogy of this unit has been discussed by Grose (1959). Presented below are brief descriptions of subunits mapped in this study.

Andesite

Rocks mapped as andesite consist of flows and flow breccias ranging from andesitic to dacitic composition. Alteration of this unit is pervasive, and individual beds and flow units can seldom be recognized.

Tuff

Highly altered and calcified tuff beds are present in the Soda Mountain Formation; they crop out as distinctive white to light-green weathering intervals 10 to 20 m thick. The rock consists of very finely crystalline quartz and feldspar (after glass fragments?) set in a calcite-rich matrix. Rock fragments 1 to 20 mm in size are common.

Quartzite

Beds of quartzite 1 to 20 m thick occur in the Soda Mountain Formation. Beds are internally parallel laminated or show large-scale (up to 2 m) cross-stratification. Quartz grains are fine-grained to medium-grained. Grose (1959) and Marzolf (1983) considered these beds to represent intermixing of Lower Jurassic Aztec Sandstone into the section.

Sandstone

Sandstone intervals ranging from 1 to 50 m thick are present in the Soda Mountain Formation. Detrital components include quartz, feldspar, and rock fragments of volcanic and sedimentary rocks. Parallel lamination and cross-stratification are the most common bedding structures.

Hypabyssal Intrusive Rocks

The Soda Mountain Formation is intruded by numerous hypabyssal intrusive rocks having compositions similar to the volcanic rocks in the Soda Mountain Formation. The hypabyssal rocks are differentiated from flows because they are usually more resistant, less fractured, and contains no preferred mineral orientations. Contacts with country rocks are locally sharp and irregular, but often are obscured by alteration. Dikes of hypabyssal rocks cutting the Silver Lake Formation may have been feeders to the flows.

Cretaceous Intrusive Rocks

Three different varieties of Cretaceous intrusive rock were differentiated: felsite, K-spar porphyry, and quartz monzonite. There is a complete variation between felsite and K-spar porphyry, and the two locally grade into one another. We consider these rocks to be essentially coeval because of fault-intrusion relations: the intrusions variously cut and are cut by faults that are considered to be contemporaneous. Quartz monzonite has been correlated with the middle Cretaceous Teutonia quartz monzonite (Groser, 1959; Larsen and others, 1958). Hence, all these intrusive rocks are assigned a Cretaceous age.

Structural Geology

Three periods of Mesozoic deformation are present in the Spectre Spur map area. The first involved folding and shearing of the Paleozoic and Mesozoic sequence. The second and third were periods of low-angle and high-angle faulting, respectively, that were roughly coeval with intrusion of the Teutonia quartz monzonite and associated hypabyssal rocks. The Cenozoic structural development of the area and will not be discussed here, since it was dealt with by Grose (1959).

The first period of deformation in the area involved mesoscale folding of the Paleozoic and Lower Triassic sedimentary rocks, and penetrative deformation of the Paleozoic section. Folds developed during this stage have amplitudes of 1 to 30 m, are tight to isoclinal, and usually have axial planes parallel to bedding or compositional layering. Fold axes are shallowly dipping to both the north and south. Cambrian to Pennsylvanian rocks on the west side of Spectre Spur, and presumed Mississippian and Pennsylvanian rocks on the east side, are most strongly deformed, and original bedding locally has been completely transposed, especially in the lower parts of the section. The Soda Mountain Formation does not show evidence of this event, presumably because its composition and bedding style combine to make it a relatively strong unit (compared to limestone and dolostone). The section may have been tilted eastward at this time.

The next period of deformation is characterized by low-angle normal faults. These faults dip gently to the west, and their hanging walls have moved relatively westward. Grose (1959) recognized some of these faults and attributed them to Nevadan-Laramide thrusting. Through the better understanding of the stratigraphy, we now are sure that these are normal

faults and not thrusts. Grose also recognized that movement preceded intrusion of the Teutonia quartz monzonite. Some of the high-angle, northeast-trending faults may have been active at this time and have served as transfer faults related to movement on the low-angle faults. Of course, the assumption made here is that there has not been significant rotation of the area after the low-angle faults were active; all structures are described in their present geometry.

The low-angle faults are cut by northeast- to east-trending moderate- to high-angle faults. Movement on these faults was probably coeval with intrusion of felsite and K-spar porphyry, as the intrusive rocks variously intrude the faults and are cut by them. Paleozoic rocks in the center of the area were uplifted during this stage of faulting. These faults are cut by north-south faults on the east and west sides of the range. However, these north-south trending faults do not extend far to the north, at least where relations are clear on the east side; hence, some movement occurred on both sets of faults at the same time, creating an uplifted block of Paleozoic rock in the center of the area. Movement on the north-south faults was principally prior to intrusion of the quartz monzonite, although the intrusion is locally cut by these faults.

Regional Significance

Three features of the Soda Mountain stratigraphy are of regional importance: 1) Devonian rocks resting unconformably on Cambrian rocks; 2) Lower Permian rocks are in turbidite facies; and 3) Lower Triassic calcareous sedimentary rocks contain conglomerate with igneous clasts.

Devonian rocks apparently equivalent to the Sultan Limestone rest on the Cambrian Nopah Formation. This is not surprising, but confirms relations seen in other deformed areas; Devonian rocks rest on Cambrian rocks in the Avawatz Mountains directly to the north (Spencer, 1981) and in the Old Dad Mountains to the south (Dunne, 1977).

The presence of Lower Permian turbidites is important because the area affected by late Paleozoic deformation and continental-margin reorganization can be extended south to the Soda Mountains from the Death Valley area (Stone and Stevens, 1984). The rocks in the Soda Mountains indicate that truncation of the continental margin (Hamilton and Myers, 1966) was felt well into the Cordilleran belt.

Lower Permian rocks are overlain unconformably by the Early Triassic Silver Lake Formation; however, the Permian rocks were not penetratively deformed prior to Silver Lake deposition (as inferred by Burchfiel and others, 1980). This helps constrain the area affected by Late Permian metamorphism to areas farther to the west (Burchfiel and others, 1980; Miller, 1981; Miller and Sutter, 1982). However, the presence of gneissic clasts in the Silver Lake Formation indicates that Precambrian crystalline rocks may have been brought to the surface locally, and that Late Permian or earliest Triassic deformation occurred in the area. Igneous clasts may imply that magmatic-arc activity extended farther east than can now be demonstrated in stratigraphic sections.

Measured Section - Silver Lake Formation

Overlying rocks of Soda Mountain Formation. Contact conformable but commonly faulted. Basal unit is green-weathering andesitic volcanic rock

Total thickness of Silver Lake Formation 229.8 m

Top of section

Red-weathering siltstone with orange-weathering calc-silicate rock at base in contact with limestone. Unit is generally thinly laminated and massively bedded. Sedimentary and internal bedding structures include low-angle bedding truncation, small-scale ripple marks, parallel lamination, mudcracks with infilling, burrow marks, and green reduction zones. Generally calcareous in lower part and iron-rich and feldspar-bearing in upper part. 70.0 m

Cherty limestone with silicified streaks. At base 3 cm red siltstone layer. 1.0 m

Red siltstone, locally sheared and with obvious micaceous sheen. Folded and strained. Some horizons contain feldspar. 6.7 m

Structurally disrupted interval with repetition of section. Section measuring resumed at base of presumed equivalent siltstone unit.

Cherty limestone, same as above. 1.3 m

Red-weathering siltstone. Sedimentary structures include parallel and low-angle cross-stratification, and erosional pockets. More calcareous and green-weathering near base and top. Some layer-parallel folds present. 28.0 m

Medium-gray to light-gray weathering cherty limestone. Chert in 3 cm to 1 m long blebs up to 10 cm thick. Siliceous streaks are present throughout the unit. 2.5 m

Green- to-orange weathering siltstone. Orange-weathering beds are coarser grained than green-weathering ones. Thinly and parallel laminated. 6.0 m

Limestone in 2 massive beds. Cherty in lower part of lower bed, and throughout upper bed. 2.5 m

Orange-weathering silty limestone. Thinly laminated to massive. Two thin conglomerate beds. 6.7 m

| | |
|---|--------|
| Dark-gray to light-gray-weathering cherty limestone. Bedded on centimeter scale, and laminated 1-10 mm. Chert in beds and bands about 2 cm thick. | 2.5 m |
| Red-weathering siltstone. Climbing-ripple and parallel lamination common, as well as small-scale cross-bedding. Laminated 2-20 mm. | 9.0 m |
| Conglomerate and sandstone. Clasts include limestone, siltstone, silty limestone, possibly tuffaceous (?) rocks and chert. Clasts of fusulinid bearing limestone are common. Fining-upward unit, conglomerate at base and sandstone at top. Clasts pebble to cobble size. | 3.7 m |
| Channelized conglomerate with clasts up to 50 cm. Pebbles 2-5 cm most common. Clasts include mainly limestone, chert, siltstone. Interbedded silty limestone and pebble conglomerate are common. | 3.0 m |
| Interbedded silty limestone and calcareous siltstone. Unit weathers red and orange. Unit is bedded about 20 cm thick. Beds of pure limestone are locally present. Green siltstone is common in the upper part of the unit. | 15.8 m |
| Limestone and siltstone. Limestone is cream-weathering and contains small gastropods. Siltstone is interbedded with the limestone and is green weathering. Thickness of this unit is uncertain because of folding at this point in the section. | 8.5 m |
| Limestone and silty limestone with local shale horizons. Limestone and silty limestone weather in irregular beds. Ammonoid coquina is common and accounts for ropy nature. Bedding about 20 cm thick. Bioturbated and intraformational conglomerate layers occur. Limestone beds near the top of the unit contain gastropod and bivalve fragments. Top 3 m of this unit is green siltstone with 5-10 mm partings. | 26.0 m |
| Reddish-weathering siltstone. Massive and featureless. Partings have micaceous sheen, and pencil cleavage is developed. | 7.6 m |
| Siltstone and limestone. Siltstone lacks abundant calcareous material and limestone occurs as discrete beds. Parallel lamination is common, and cleavage with micaceous sheen is well developed. Upper 5 m is mostly pure siltstone. | 19.8 m |
| Massive pink siltite. | 1.0 m |
| Brown-weathering silty limestone. Thinly laminated. | 4.6 m |
| Thin disrupted interval. | |

Channelized conglomerate. Mainly composed of intraformational edgewise conglomerate. Clasts include silty limestone, limestone, chert, and volcanic rocks. Pink siltstone and limestone occur as thin interbeds.

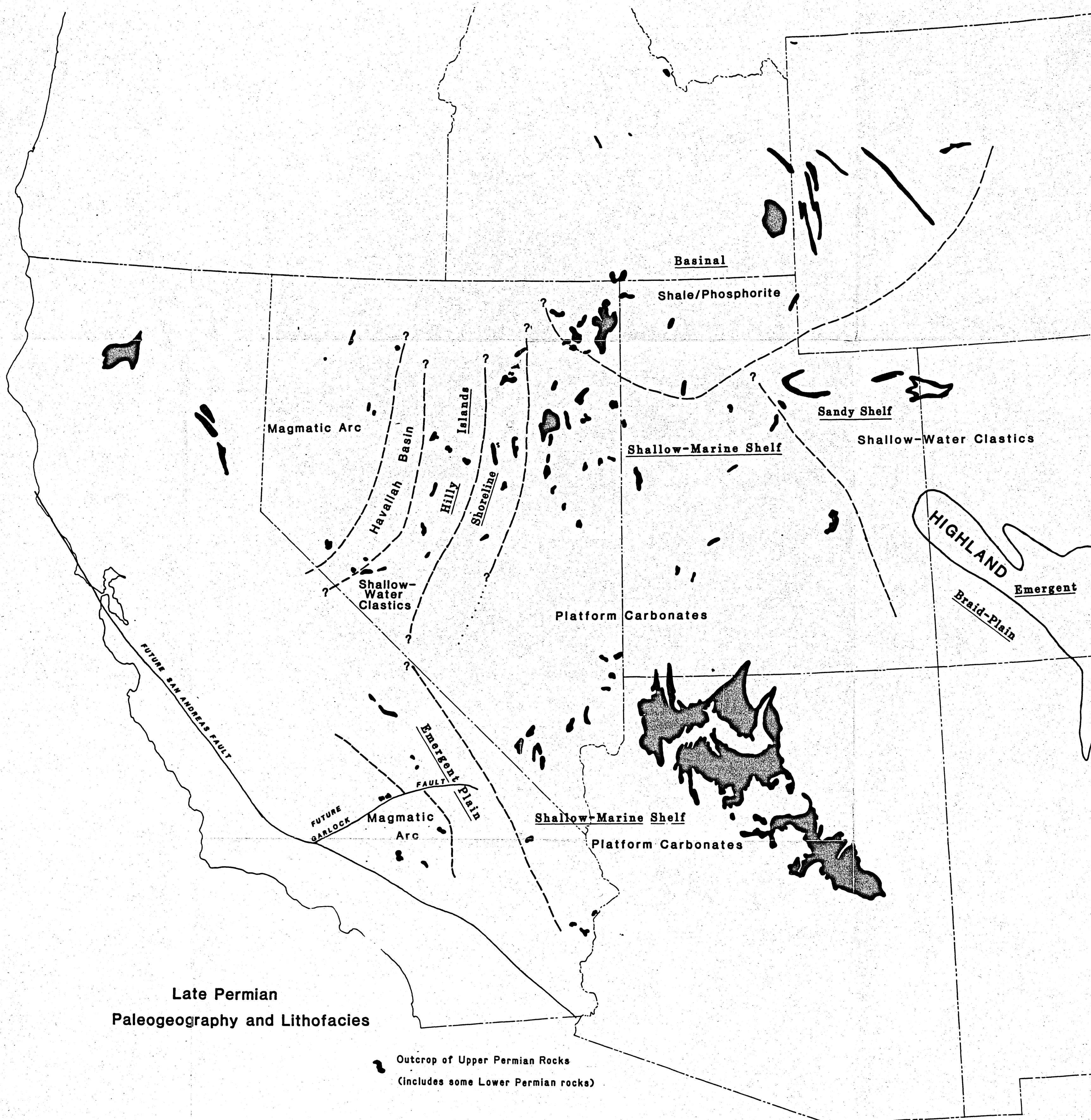
3.0 m

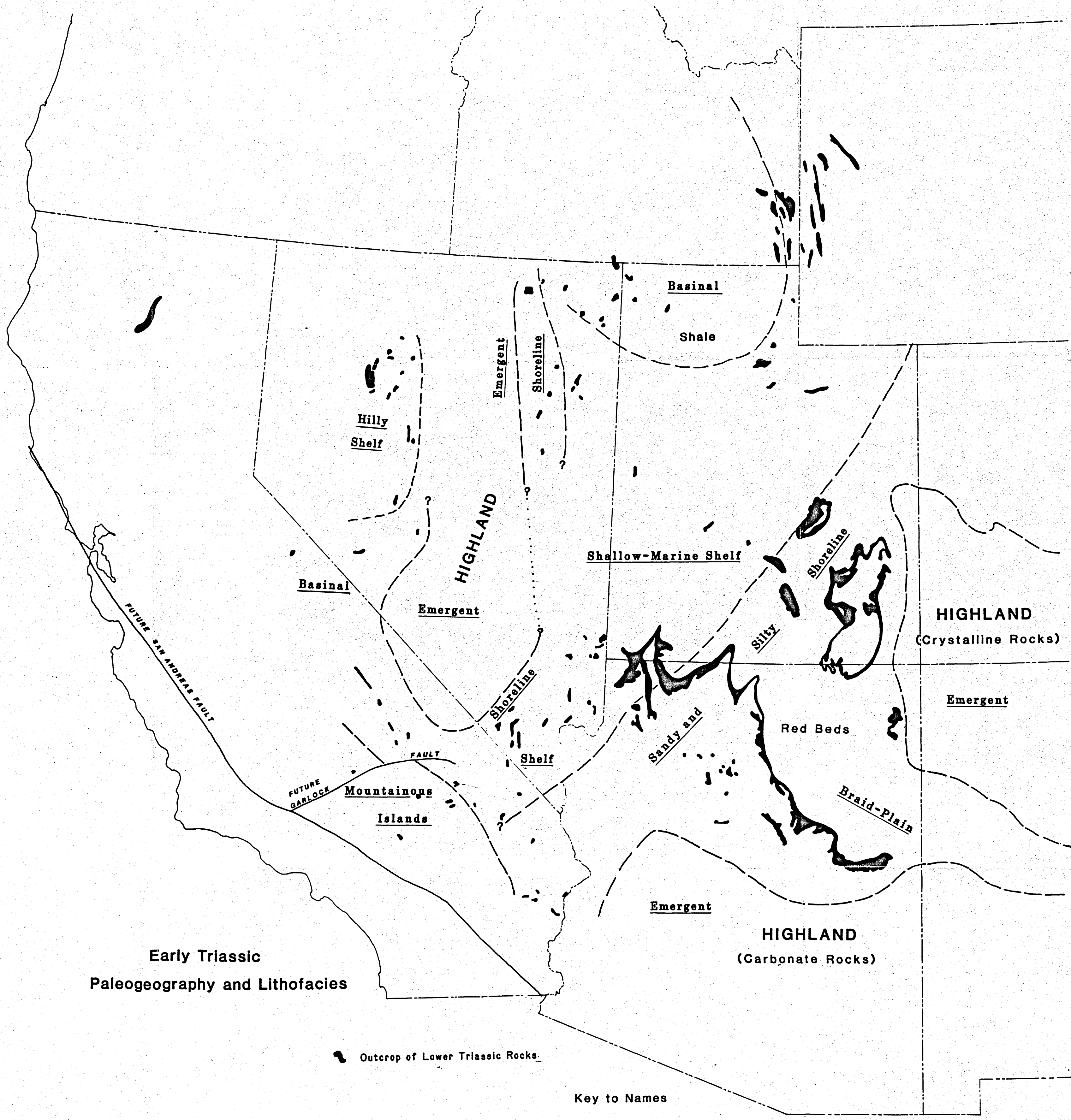
Black limestone. Pure limestone with stringers of pink siltite about 5 mm thick. Bedding about 20 cm.

0.6 m

Base of section.

Permian limestone and calcareous siltstone. Conodonts recovered from bed 1 m below contact are Neostreptognathodus Ruzencevi (Kosuz) (late-early Leonardian).





Early Triassic
Paleogeography and Lithofacies

● Outcrop of Lower Triassic Rocks

Key to Names

Clastics -- Lithofacies

Basinal -- Paleogeographic Element

| | | | |
|---------------|---|--------|---|
| Quaternary | { | Qa | Alluvium |
| Cretaceous | { | Kf | Felsite |
| | | Kk | K-Feldspar Porphyry |
| | | Kq | Quartz Monzonite |
| Jurassic | { | JRsq | Soda Mountain Formation: Quartzite |
| | | JRsh | Hypabyssal Intrusives |
| | | JRss | Sandstone |
| | | JRst | Tuff |
| | | JRsa | Andesite |
| Triassic | { | Trsl | Silver Lake Formation |
| Permian | { | Pt | Marble and Calc-silicate Sequence |
| Pennsylvanian | { | PPbs | Bird Spring Formation |
| Mississippian | { | MmPPbs | Monte Cristo Limestone, Bird Spring Formation Undivided |
| | | Mm | Mm: Monte Cristo Limestone |
| | | Mb | Mb: Bullion Member |
| | | Ma | Ma: Anchor Member |
| | | Md | Md: Dawn Member |
| Devonian | { | MmDs | Monte Cristo Limestone, Sultan Limestone Undivided |
| | | Ds | Sultan Limestone |
| Cambrian | { | Cn | Nopah Formation |

CONTACTS

Definite, approximate.

FAULTS

Low angle normal faults, ticks on upper plate, arrow indicates dip direction.

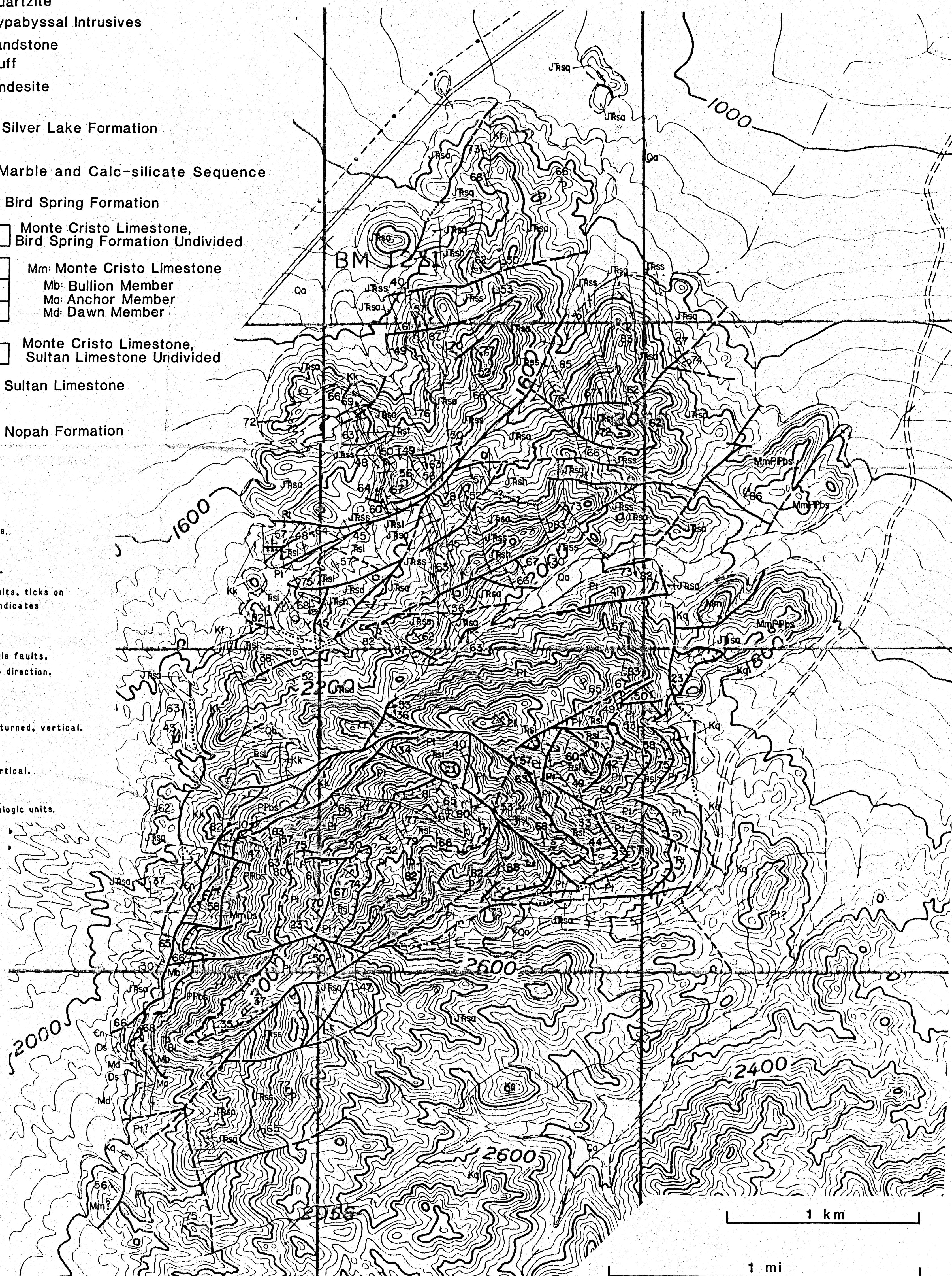
Moderate to high angle faults, arrow indicates dip direction.

ATTITUDES

Bedding: Inclined, overturned, vertical.

Foliation: Inclined, vertical.

Field connector for lithologic units.



Geology by J. D. Walker (1983)

U.S.G.S topographic base Baker 15' quadrangle
60' contour interval